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THE OPTICS OF THE SPECTROSCOPE

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1. Lord Rayleigh's investigations on the resolving power of prisms and gratings have enabled us to calculate the theoretical efficiency of any spectroscope. When those researches were published, I was at work investigating spectra of feeble intensities which rendered it necessary to open the slits considerably beyond the point at which Lord Rayleigh's equations became applicable. It was not quite clear that with a wide slit the resolving power, as distinguished from dispersion, remained the sole determining factor in the calculation of the efficiency of spectroscopes, but I proved this to be the case.[1] It seemed convenient to introduce a new quantity, which I called the "purity" of a spectrum, and which was intended to serve as an indicator for the efficiency of the instrument with wide slits, just as the resolving power was the indicator for narrow slits. Making a certain assumption as regards the condition of resolution and writing

$$P = \frac{\lambda}{\lambda + d\psi} R, \qquad (1)$$

where P is the purity, R the resolving power, ψ the angle subtended by the diameter of the collimator lens at the slit, d the width of the slit, and λ the wave-length, I showed that two wave-lengths differing by $\delta\lambda$ were resolved when $\delta\lambda = \lambda/P$.

[1] Art. "Spectroscopy," *Encyclopædia Brittanica*.

Shortly afterward Professor Wadsworth subjected equation (1) to a criticism which in the main was justified, and he entered into an elaborate discussion of the whole problem. In the course of his analysis he arrived at the paradoxical result that there is a certain width of slit for which its power to resolve close doublets is greatest, so that if the slit be narrowed beyond that width, resolving power is diminished.

Elementary considerations show that this result cannot be correct, but, as it has never been publicly challenged, and has been reproduced in Kayser's *Handbuch*, it may be useful to disprove it formally. In Fig. 1 let the curved line represent the distribution of intensity in

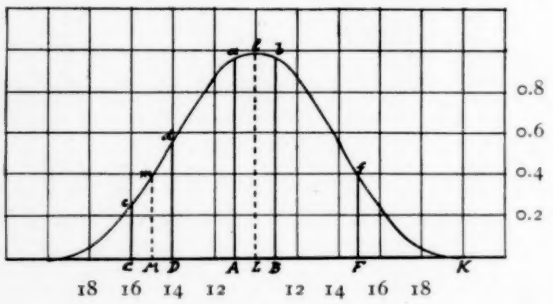

FIG. 1.

the diffraction image of an indefinitely narrow slit, and let *Aa* and *Bb* be the positions of geometrical images of the two edges of the slit, the diffraction image being considered to lie in the focal plane of the telescope, which also contains the geometrical image of the slit. If the slit be widened or narrowed symmetrically, the intensity in the central line of the diffraction image is easily shown to be proportional to the area *ABba*. On the same scale, the area *CDdc* would represent the intensity of the image along its central line *Mm*.

Lord Rayleigh has found that with a narrow slit two close lines are fairly resolved by means of eye observations when they are at such a distance from each other that the center of one diffraction image falls on the first zero of intensity of the other. If in Fig. 1 the center of a second diffraction image is at *K*, the distribution of light in the combined images has a minimum along a line *Ff*, where *F* is half-way between *L* and *K*. The intensity along this line is 0.81 of

the maximum intensity, and Professor Wadsworth takes this fraction to be in all cases that required for the intensity at the minimum, if the lines are to be resolved. Accepting this criterion, consider the effect of widening the slit on the distribution of intensity in the diffraction image of a single line. If at any point of the intensity-curve the outline *cmd* were a straight line, the intensity at that point would vary in exact proportion to the width of the slit. Neglecting, therefore, the curvature at all points, the distribution of intensity would not be altered by a change in the width of the slit. But when the curvature is taken into account, the increase in intensity is more or less rapid than the increase in the width of the slit, according as the curve is convex or concave when looked at from the axis of abscissæ. Near the central line the concavity is greatest, and diminishes toward the two sides; hence it follows that the central intensity increases less with a widening of the slit than the intensity at any other part of the diffraction image. If two lines are at such a distance that with a very narrow slit they are just resolvable, the ratio of the minimum to the maximum is $2Fj/Ll$. As widening the slit has just been shown to increase the intensity at Ll less than that at Fj, this ratio must be increased; and if the lines were just on the point of resolution with a narrow slit, they cease to be resolved when the slit is widened.

In order to show where the error in Professor Wadsworth's treatment occurs, I have plotted in Fig. 2 the curve AC_1B which is represented by his formula, the ordinates standing for the distances of the two components of a doublet which is just on the point of resolution, and the abscissæ denoting the widths of the slit. The unit of length in both cases is half the width of the central diffraction band. The drop in the curve between A and C_1 shows the improvement in resolution which is indicated by Professor Wadsworth's formula. But the curve ACB, which has been drawn by means of accurate calculation, gives a steady diminution of resolving power with increased width of slit. This is as it should be. Professor Wadsworth obtained his formula by interpolation between four points. Of these A is one, the second is at the point marked P in the figure, and the two others were at the positions calculated for slits twice and three times as great as that to which P refers. The minimum given by his formula has been obtained simply in consequence of an arbitrary manner of

interpolation. No one joining the points B_1 and A would, of course, do so by means of a curve having, without any apparent reason, a dip at C_1. Professor Wadsworth was misled by not plotting the distance of resolution, but this distance diminished by the slit-width. This explains his paradoxical result.

2. Although Professor Wadsworth has brought out many interesting points in the course of his investigations, he has, in my opinion,

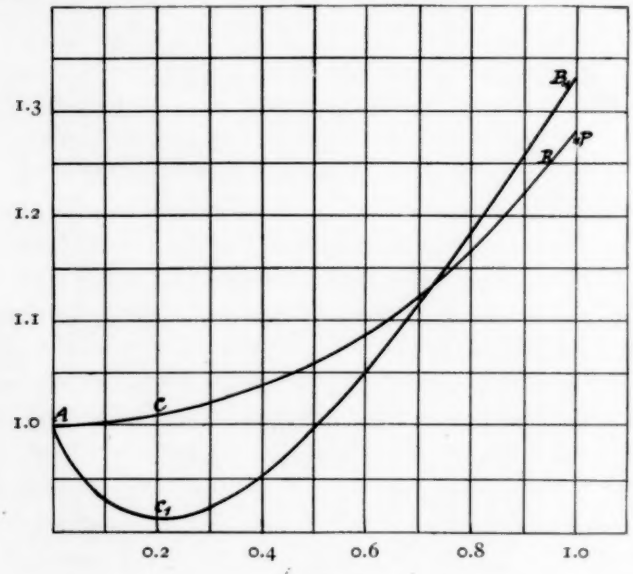

FIG. 2

done harm by depriving the subject of its original clearness and simplicity. It seems therefore necessary to start afresh by asking ourselves what objects a theoretical discussion on resolving powers may usefully serve. There can be no doubt as to the fundamental value of Lord Rayleigh's original equations. They allow us to compare the efficiency of gratings and prisms, or again of large and small prisms. When we have solved in our minds what kind of resolving power is wanted, we may without difficulty construct an instrument which shall fulfil the requirements. Great refinement of accuracy is not necessary for the purpose, nor is it possible, because other circumstances come into action, notably luminosity. My own investigations of very weak spectra led me, as already men-

tioned, to introduce the question of slit-width. Although I think I was justified to do this, I have often regretted it, because I set the ball rolling, and it went on rolling, but unfortunately in the wrong direction. Professor Wadsworth, for instance, extended my equation by including the case that each component of the doublet which is to be resolved is not quite homogeneous and includes a finite range of wave-lengths. This meant throwing the whole question into confusion. When we discuss the power of an instrument, we must clearly separate those conditions which concern the instrument from those which do not. No one would think of asserting that the power of a telescope is less when it tries to distinguish details in a nebula than when it examines close double stars, for the telescope is not responsible for the absence of sharp detail in a nebula. Its object is to give images as nearly corresponding to reality as possible, and the extent to which that object is realized depends purely on instrumental conditions. Similarly, the main object of a spectroscope is to form a pure spectrum, and the extent to which that object is realized depends on the prisms or gratings and on the width of the slit, and on nothing else. The separation of double lines is a convenient test of resolving power, but the main purpose of the spectroscope is the correct representation of the distribution of energy in a spectrum, whether continuous or discontinuous. I do not deny the utility of investigating under what conditions bands of finite width are resolved, but the discussion should be kept clear of all connection with formulæ representing resolving powers.

Owing to the finiteness of the waves of light, each wave-length, even in a so-called pure spectrum, encroaches to some extent on a neighboring one. We require some kind of simple measure as to the extent of this trespass. In my first treatment of the subject I endeavored to obtain this by neglecting everything in the diffraction image beyond the first band. If that were allowable, each wave-length would spread over a certain finite range and not beyond. If 2ϵ be the width of the first band in the diffraction image of a narrow line, and σ the width of the slit-image, each wave-length would spread through a distance $\frac{1}{2}\sigma+\epsilon$ to either side of its center. Two lines would be completely separated when their distance is $\sigma+2\epsilon$. But Lord Rayleigh showed that in the case of nearly homogeneous lines the

resolution is already noticeable when their distance is ϵ. I therefore made the assumption, which seemed to me to be the most simple one to make, that with wide slits resolution begins when the distance between the lines is $\sigma+\epsilon$. Equation (1) is deduced under this condition. Professor Wadsworth showed conclusively, however, that, owing to the rapid falling off of the light near the edge of the image of an extended luminous surface, the distance between lines may be appreciably reduced beyond the point at which, according to my formula, resolution should begin. This rapid diminution in intensity may be understood at once, if it be remembered that at the edge of the geometrical image of a surface the intensity is already reduced to one-half, so that it requires very little separation between the geometrical images of two surfaces to produce a sensible diminution of light between them. Though equation (1) may therefore serve to give a rough and ready expression of purity, it gives incorrect results when the resolution of narrow doublets is in question. Professor Wadsworth's test of resolution, that the intensity at the point half-way between the centers of the overlapping lines shall be a definite fraction of the intensity at the center of each of the images, has the disadvantage that it is based on visual observation, and is not necessarily applicable directly to photographic or bolometric measurements. If I have left the criticism of Professor Wadsworth's results stand over for so long a time after their appearance, it was chiefly because I was not quite satisfied with any way of reconciling the different considerations of which account has to be taken. After much hesitation, I wish now, however, to submit the following proposals, which seem to me to meet the case in a fairly simple manner, and have the advantage of keeping Professor Wadsworth's criterion in practice while putting its definition on a somewhat wider basis.

In the image of a very narrow slit the intensity at a distance ϵ from the center is zero; the intensity at a distance $\frac{1}{2}\epsilon$ is 0.40528 that of the center. We may therefore say that the line spreads out on either side to a point which is at a distance twice that of the point at which the intensity is equal to the above fraction. Let us generalize that definition and say: The sensible image of a slit of finite width spreads through a distance δ to either side of its center, such that the intensity at a distance $\frac{1}{2}\delta$ is 0.40528 that of the intensity at the center.

Two lines at a distance 2δ from each other may then be said to be completely resolved, inasmuch as their wave-lengths do not trespass sensibly on each other.

Observation shows however, that visual resolution already begins when their distance is δ. We shall adopt this distance as the criterion of visual resolution.

If a point of the spectrum defined by λ is encroached upon according to the above definition by waves on either side as far as $\lambda+\delta\lambda$ and $\lambda-\delta\lambda$, we write

$$P=\lambda/\delta\lambda,$$

and call P the purity of the spectrum. Two lines will be *completely* separated when they are at a distance $\delta\lambda$, which is equal to $2\lambda/P$, and visual resolution begins when their difference of wave-length is λ/P.

For very narrow slits the equations are the same, but the resolving power R replaces the purity P. Purity is proportional to resolving power, but also depends on the width of the slit. If we write

$$P=pR \qquad (2)$$

p may be called the purity factor. Its values for different widths of slit are given in Table III.

The only thing that is arbitrary in the above definitions is the fixing of a definite limit to which wave-lengths spread on either side, as this implies the neglect of all light which lies beyond these limits. But some arbitrary convention is necessary, and we are justified in giving up purposely refinement of accuracy in order to obtain a ready guidance in our choice of instrument and of width of slit. From this point of view, I cannot find any simpler definitions than the ones chosen.

I do not think it will be necessary to introduce other factors for photographic or bolometric investigations. In the case of the bolometer much depends on the manner in which that instrument is applied. It is beside the mark to say that the bolometer can detect smaller differences of intensity than the eye, because it is a question, not only of observation, but also of interpreting the observations. Supposing there is a falling off in intensity at any point in the spectrum, we do not know whether to interpret this as due to a partially overlapping doublet, or to a narrow band having a minimum of light

at the place where the falling off is observed. After all, the test of resolution usually applied presupposes that we know beforehand that we are dealing with a doublet. If that is not the case, we must increase the power until the resolution is complete. This consideration only shows once more that refinement is impossible. If the performances of different instruments, or of the same instrument with different widths of slit, are to be compared, the reduction of intensity chosen as a test of resolution may be altered within wide limits without detracting from the values of the indications it gives. We fix the fraction once for all for the sake of convenience, and may adopt the same number whether the registration is visual, photographic, or radiometric. We may then discuss whether in particular cases resolution is obtained more or less readily in practice than according to formula (2).

3. The suggested definition, as already pointed out, implies the neglect of a certain amount of light. For narrow slits the light neglected is approximately that which lies beyond the central diffraction band. It may therefore be of interest to determine how much of the total light is actually concentrated in that band. Table I gives the numbers representing the intensity of successive bands. The second column gives the energies of light in half the first band and in each

TABLE I

Order of Band	Relative Intensities		Sum of Intensities Total Light = 1
	Total Light = π	Total Light = 1	
Half first band	1.41843	0.45150	0.90300
Band 2	.07401	.02356	.95012
Band 3	.02587	.00824	.96660
Band 4	.01310	.00417	.97494
Band 5	.00790	.00251	.97996
Band 6	.00528	.00168	.98332
Band 7	.00378	.00120	.98572
Band 8	.00283	.00089	.98750
Band 9	.00220	.00070	.98890
Band 10	.00176	.00056	.99002
Band 11	.00144	.00046	.99094
Sum	1.55660	.49547	.....

Note.—The number given in the first row of the last column represents the energy of the light in the whole of the first band, and the other numbers in the same column include the energies of both bands of the same order.

successive band, while the third column gives the total energy of the central and lateral bands up to and including the two which are of the order marked in the first column. It is seen that 90 per cent. of the light goes to form the central band, that 2 per cent. goes to form the bands of higher order than the fifth, and that 1 per cent. of the total light goes to form the bands of higher order than the eleventh.

Although a considerable amount of light is therefore neglected in our convention as regards the extent of trespass, yet no practical disadvantages result therefrom, especially as the light neglected is spread over a considerable range of wave-lengths, so that within any small range of periods the total energy is exceedingly small.

4. If σ is the width of the geometrical image of the slit measured in a certain unit, and x the distance in the same unit from the central line of the image, the intensity in the diffraction image of the slit at the distance from the center x is

$$\int_{x-\frac{\sigma}{2}}^{x+\frac{\sigma}{2}} \alpha^{-2} \sin^2 \alpha \, d\alpha \tag{3}$$

The unit distance here is such that the first minimum with an indefinitely narrow slit occurs when $x = \pi$.

I have calculated a table of the integral

$$\int_{0}^{x} \alpha^{-2} \sin^2 \alpha \, d\alpha \quad ,$$

where x was gradually increased by steps of 0.1π from 0 to 5π. By means of this table, which it is not necessary to reproduce here, the integral (3) could be calculated for different values of σ and x. Table II giving the distribution of light for different slit-widths was thus obtained. The scale of distance in this table has been changed so that the distance previously represented by π is now unity. To reduce to centimeters we should have to multiply all quantities by $f_1\lambda/D_1$, where f_1 and D_1 are the focal length and diameter of the telescope. The slit-widths as given in the headings of the columns are given in terms of the slit-factors to be defined presently. They may be reduced to centimeters by multiplication with $f\lambda/D$, where

TABLE II

DISTRIBUTION OF INTENSITY IN IMAGES OF SLITS OF FINITE WIDTH

The unit of distance is the half-width of the central diffraction band in the focal plane of the telescope. The width of slit corresponding to the headings of the different columns is obtained by multiplying the numbers given, with the product of the wave-length and focal length of collimator and dividing by the diameter of the collimator lens.

Distance from Center	$\sigma=0$	$\sigma=0.8$	$\sigma=1.6$	$\sigma=2.4$	$\sigma=3.2$	$\sigma=4.0$	$\sigma=8.0$	$\sigma=12.0$
0	1	1	1	1	1	1	1	1
0.1	0.9675	0.9680	0.9695	0.9719	0.9752	0.9792	0.9999	0.9994
.2	.8751	.8770	.8825	.8916	.9040	.9192	.9983	.9978
.3	.7368	.7406	.7518	.7702	.7954	.8265	.9917	.9962
.4	.5728	.5785	.5956	.6239	.6627	.7108	.9753	.9952
.5	.4053	.4126	.4345	.4708	.5209	.5834	.9441	.9949
.6	.2546	.2627	.2872	.3276	.3845	.4560	.8946	.9946
.7	.1353	.1434	.1676	.2082	.2652	.3384	.8252	.9918
.8	.0547	.0617	.0830	.1190	.1705	.2379	.7374	.9831
.9	.0119	.0173	.0336	.0618	.1030	.1588	.6356	.9640
1.0	0	.0034	.0138	.0325	.0610	.1017	.5261	.9306
1.1	.0080	.0095	.0143	.0237	.0395	.0646	.4166	.8797
1.2	.0243	.0243	.0247	.0266	.0320	.0436	.3146	.8105
1.3	.0392	.0384	.0362	.0334	.0319	.0339	.2261	.7243
1.4	.0468	.0457	.0427	.0383	.0338	.0308	.1550	.6252
1.5	.0450	.0442	.0420	.0385	.0343	.0304	.1027	.5190
1.6	.0358	.0356	.0349	.0337	.0321	.0302	.0681	.4128
1.7	.0230	.0233	.0244	.0259	.0274	.0287	.0481	.3136
1.8	.0108	.0116	.0139	.0174	.0216	.0258	.0387	.2272
1.9	.0027	.0036	.0064	.0108	.0162	.0221	.0356	.1575
2.0	.0000	.0008	.0033	.0072	.0123	.0181	.0352	.1059

$\sigma = \frac{4dD}{\lambda f}$

by R.C.W. 1939.

f and D are the focal length and diameter of the collimator lens. Having therefore measured a slit-width, d, we calculate $4dD/f\lambda$. The distribution of light is then found in the vertical column headed by the number thus calculated. The intensities are all given in terms of the intensity at the center of the image.

Having found the distribution of light, we determine the factor of purity by finding in the first instance the distance at which the intensity is equal to 0.40528. This I did by a process of interpolation, using finite differences. Doubling the distance thus calculated, we obtain the distance of resolution. The results are collected in Table III. The unit distance is again half the width of the central diffraction image when the slit is indefinitely narrow. Column I gives the width of the slit in this unit.

It is of advantage to refer all slit-widths to some one width conveniently chosen and called the "normal width." In investigating

TABLE III

CONNECTION BETWEEN PURITY AND WIDTH OF SLIT

I Width of Slit	II Slit Factor	III Distance of Resolution	IV Purity Factor	Relative Intensities	
				V Intensity 1 for Normal Width	VI Intensity 1 for Infinite Width
0	0	1.0	1.0	0	0
0.1	0.4	1.002	0.998	0.406	0.100
.2	.8	1.009	.991	.805	.198
.25	1	1.014	.986	1.000	.246
.3	1.2	1.021	.980	1.191	.293
.4	1.6	1.038	.964	1.558	.383
.5	2.0	1.060	.943	1.902	.467
.6	2.4	1.089	.918	2.217	.545
.7	2.8	1.124	.889	2.500	.615
.8	3.2	1.168	.856	2.751	.676
.9	3.6	1.221	.819	2.967	.729
1.0	4.0	1.283	.780	3.148	.774
1.2	4.8	1.438	.695	3.415	.839
1.4	5.6	1.624	.616	3.571	.878
1.6	6.4	1.823	.549	3.646	.896
1.8	7.2	2.022	.495	3.670	.902
2.0	8.0	2.221	.450	3.674	.903
3.0	12.0	3.214	.311	3.789	.931
D very large		D+0.096		4.0689	1.000

The width of slit in centimeters is obtained by multiplying the first column with λ/ψ, where ψ is the angle subtended by the diameter of the collimator lens at the slit.

the question of deterioration of images owing to aberrations or other defects, Lord Rayleigh has generally admitted one-quarter of a wavelength as the limit of the allowable deviation from the ideal wavefront, if the image is not to suffer appreciably. Looked at from this point of view, an extreme difference of path of one-quarter wavelength from one of the edges of the slit to the nearest and farthest points of the collimator lens should give images as good as if the slit were an indefinitely narrow line. Consequently, we may fix on this width as being that of the normal slit. I call "slit factor" the width of a slit expressed in terms of the normal slit. These factors are entered in Column II of the table. Column III gives the distance of resolution, which, for an infinitely narrow slit is unity; column IV gives the purity factors, which are equal to the reciprocals of these distances of resolution. This column therefore expresses what fraction of the highest possible resolving power is retained under

different conditions of slit-width. In Column V of Table III I have given the central intensities of the images in terms of the intensity for the normal width of slit, while Column VI gives the same intensities in terms of the possible maximum intensity, which is that obtained with an infinitely wide slit. A comparison of Columns IV and V will help in each case to determine our choice as regards width of slit. The normal slit, for which the slit factor is unity, will be seen to give us a resolving power about 1.5 per cent. less than the maximum power. If we do not mind a loss of purity of 6 per cent. we may set the slit at 2, and obtain nearly double the amount of light. We may treble the light, retaining about 80 per cent. of purity, but a total intensity of 3.67 times that obtained with a normal slit is accompanied by a loss of half the resolving power. When this point has been reached, a further widening of the slit leads to a great deterioration of purity without material increase of light. It will, however, appear presently that the loss of light due to diffraction renders a further slight increase of resolving power advisable.

We are led to the general conclusion that spectroscopes intended for observations in which light is a consideration should be constructed so as to give about twice the resolving power of that actually aimed at. We may then set the slit so that its factor is 7.2.

It is somewhat remarkable that the one statement in my previous treatment of purity and resolving power which, though frequently quoted, has never been challenged, is the only one which is really wrong. I stated that the intensity at the center of the diffraction image increases with the widening of the slit until the slit-image had a width equal to one-half the width of the diffraction image. This was an error. I was then writing under the supposition that all the light beyond that contained in the central band may be neglected, and if that is the case, the light increases until the slit-image has a width equal to that of the width of the diffraction image, or double the width given in my statement. The slit-factor in that case would be 8. Taking account of the light which forms the lateral bands, the increase in intensity must of course go on indefinitely with an increase in the width of the slit. Table III shows, however, that this increase is very slow if the slit-factor is greater than about 7.

The following statement in my *Encyclopædia* article has also been

criticised: "As a matter of fact, spectroscopists generally work with slits wider than that which theoretically gives full illumination. The explanation of the fact is physiological, visibility depending on the apparent width of the object."

The width of slit necessary for full illumination was, as pointed out above, underestimated, and this no doubt partly accounts for the discrepancy alluded to in the passage quoted. But the physiological effect was not invented, as my critics seem to have believed, to serve as an explanation *ad hoc*, but it is a *vera causa*, and should be familiar to spectroscopists accustomed to eye-observations. Let those who doubt hunt for the violet potassium line in a Bunsen burner, and, when found, measure the width of the slit they have used.

5. The above investigation is based on the supposition that the slit behaves like a self-luminous source, each part of which acts independently of the other. In laboratory experiments this may be secured by forming an image of the source of light on the slit. When the slit is narrow, the condensing lens must subtend a larger angle at the slit than the collimator lens, to prevent loss of light by diffraction. This loss may be very considerable, and if the slit has its normal width, the angular aperture of the condensing lens, as seen from the slit, should, if possible, be four times as great as the angular aperture of the collimator lens.

In the case of astronomical work, the angular aperture of the condensing lens is given, and to save loss by diffraction, the angular aperture of the collimator lens would have to be reduced so as to allow a wider opening of the slit. The gain would, however, be more than balanced by the loss of light due to the cutting out of the undiffracted rays coming from the outside portions of the telescope lens.

It is not quite easy to calculate the loss of light due to diffraction when a condensing lens is used. Fortunately Mr. J. H. Moore has recently published[1] experimental data which show that it is not much different from that found when a parallel beam falls on the slit. The effect of diffraction would in that case be to reduce considerably the intensity factor given in Column V of Table III for slits having

[1] *Astrophysical Journal*, **20**, 285, 1904.

a slit factor less than 8, but it would not much effect the light if the slit had that width. There is no way of avoiding this, as the width of slit is fixed by the angular aperture of the collimating lens, and that again is fixed by the angular aperture of the telescope lens. The remedy proposed by Mr. Moore of increasing the length of the collimator would not be effective unless it were accompanied by an increase of resolving power. We must face the loss of purity, and design our spectroscopes to have about two and one-fourth times the required resolving power. A slit factor equal to 8 will then give us practically as much light as can be secured.

With respect to star work, it should, however, be remembered that if definition were perfect, the slit might be dispensed with altogether. The slit in that case could only impair, but never improve, the sharpness of the spectroscopic lines. If a slit is found of advantage, it is only on account of the unrest of star images due to atmospheric causes. If the tremors of the star images are sufficiently rapid, we may consider the case covered by the previous discussion; and the observed results seem to be in agreement with this view.

THE UNIVERSITY,
Manchester, England,
December 1904.

SOME NEW DETERMINATIONS OF THE REFLECTING POWERS OF GLASS AND SILVERED GLASS MIRRORS[1]

By C. A. CHANT

I. REFLECTION FROM METALS

The question of reflecting power is of great importance from both the theoretical and the practical point of view; and it is not surprising, therefore, that numerous investigations have been made upon it. Lord Kelvin has proposed the word "reflectivity" to designate the ratio of the whole reflected to the whole incident light, and it will be used with that meaning in the present paper.

The first precise measurements were probably made by W. Herschel.[2]

He used a photometric method suggested by Bouguer,[3] and measured the reflectivity of one of his specula for nearly perpendicular incidence. He found that it returned 67.262 per cent. of the incident light.

About thirty years later Potter[4] made similar experiments. Potter made his own mirrors, and, becoming expert at polishing, he wished to compare his work with Herschel's. He noted, also, that Newton[5] had assumed that more light was reflected as the angle of incidence was increased, and he determined to test this statement.

Potter also used a modification of Bouguer's photometer, and he was astonished to find his experimental results at variance with Newton's "obvious observation." For a plane mirror of speculum metal the reflectivity at 10° of incidence was about 68 per cent., and this gradually fell for increasing incidence, becoming about 64 per

[1] Read before the Royal Astronomical Society of Canada.

[2] "On the Power of Penetrating into Space by Telescopes, etc.," *Abridgment of Phil. Trans.*, **18**, 580, 1800.

[3] *Traité d'optique.* See Priestley's *History*, p. 540.

[4] *Edinb. Jour. Sci.*, N. S., **3**, 278, 1830.

[5] Newton, in a letter to the secretary of the Royal Society, dated May 4, 1672, discusses the advantages of his form of reflecting telescope over Cassegrain's, and remarks: "For it is an obvious observation that light is most copiously reflected from any substance when incident most obliquely."—*Abridgment of Phil. Trans.*, **1**, 712.

cent. at 60°. For a mirror of cast steel the same behavior was observed, the reflectivity falling from 59 per cent. at 10° to 54 per cent. at 60°. He thus concluded that the metals reflect better at small incidences. Subsequent investigations fail to substantiate the general law enunciated by Potter.

J. Jamin[1] worked with polarized light and compared the amounts reflected from silver, steel, and speculum metal with that from glass; and, assuming the laws of reflection from glass to be accurately represented by Fresnel's formulæ, he calculated the absolute amount of light reflected from the metals at various incidences. Jamin's results to a certain extent corroborate Potter's, but the agreement is not very good. Moreover, Jamin's indirect method has been criticised by Verdet[2] as not susceptible of great accuracy. About the same time the reflectivities of metals for heat-waves were studied by de la Provostaye and Desains,[3] and the values given by them for heat-waves are approximately the same as Jamin's for light-waves.

Sir J. Conroy[4] made an extended series of experiments on metallic reflection. He used a modified form of Ritchie's photometer, in which the light falls on the receiving screens obliquely, and thus polarization effects may have influenced the results to some extent. His mirrors were of silver, steel, tin, and speculum metal. With the first three the amount of reflected light gradually increased with increasing incidence, but with speculum metal it first increased, then diminished, and then increased again. These results are at variance with Potter's, Jamin's, and the theoretical formulæ deduced by Cauchy and MacCullagh.[5]

Rayleigh[6] measured the reflectivity of silvered glass and mercury for almost perpendicular incidence. For plate glass silvered on the anterior surface the reflectivity was 93.9 per cent.; when silvered on the posterior surface, 82.8 per cent.; for mercury, 75.3 per cent.

[1] *Ann. de Chim. et de Phys.*, (3) **19**, 296, 1847.

[2] *Leçons d'optique physique*, **2** (*Œuvres*, Tome **6**), p. 546.

[3] *Ann. de Chim.*, (3) **27**, 109, 1849; (3) **30**, 159, 276, 1850.

[4] *Proc. R. S.*, **28**, 242, 1879; **31**, 486, 1881; **35**, 26, 1883; **36**, 186, 1883; **37**, 36, 1884.

[5] See Verdet, *l. c.*, pp. 563 f.

[6] *Scientific Papers*, **2**, 522, 1886; **4**, 3, 1892.

The most extensive investigations on metallic reflection, however, have been recently made by Hagen and Rubens.[1] They measured the reflectivities for perpendicular incidence of numerous metals and alloys for wave-lengths ranging from 250 to 1500 $\mu\mu$; and the general conclusion was that the reflectivity increased with the wave-length.

Work similar to this and leading to the same result has been done by Rubens, Langley, Nichols, and Trowbridge.[2]

In two still later researches Hagen and Rubens[3] have shown that for long heat-waves the amount of the radiation entering the reflecting metal (i. e., the incident light less the reflected light) and the emissive power are inversely proportional to the square root of the electrical conductivity, and also inversely proportional to the square root of the wave-length of the incident radiation. This is in accord with Maxwell's electromagnetic theory.

II. REFLECTION FROM GLASS

Potter[4] was one of the earliest workers in this field also. He experimented with crown, plate, and flint glass, determining the reflectivity of the front face and also of both faces of a plate for incidences ranging from 10° to 85°.

Since Potter's time measurements have been made by many experimenters, usually in verification of the theoretical formulæ given by Fresnel.[5]

Rayleigh[6] measured the intensity of the light reflected at nearly perpendicular incidence from three specimens of glass, and concluded that recently polished glass surfaces have a reflectivity agreeing closely with Fresnel's formula, but that after some months or years it may fall off as much as 30 per cent. without any apparent tarnish on the surface. Some years later he measured the reflec-

[1] *Ann. der Phys.*, **1**, 352, 1900; **8**, 1, 1902.

[2] H. Rubens, *Wied. Ann.*, **37**, 249, 1889. E. F. Nichols, *ibid.*, **60**, 401, 1897; *Phys. Rev.*, **4**, 297, 1897. S. P. Langley, *Phil. Mag.*, **27**, 10, 1889; *Am. Jour. Sci.*, (3) **36**, 397–410, 1888. Rubens and Nichols, *Wied. Ann.*, **60**, 418, 1897. A. Trowbridge, *ibid.*, **65**, 595, 1898.

[3] *Ann. der Phys.*, **11**, 873, 1903; *Ann. de Chim. et de Phys.*, (8) **2**, 441, 1904.

[4] *Edinb. Jour. Sci.*, N. S., **4**, 53, 1831.

[5] See Verdet, *l. c.*, pp. 395–518. [6] *Scientific Papers*, **2**, 522, 1886.

tivity of water for nearly perpendicular incidence. He used a photographic method and found the value 2.076 per cent.

Conroy[1] has also studied the amount of light reflected and transmitted by certain kinds of glass. He used three kinds, having indices (for sodium light) of 1.5145, 1.5274, 1.6330, and worked with natural light. He showed that the amount of light reflected depends to some extent on the way the glass has been polished, and that the variation from the amounts calculated by Fresnel's formulæ is sometimes an excess, sometimes a defect. He found, too, that the surface of flint glass, after repolishing, seems to alter somewhat readily; while with crown glass the change, if any, proceeds very slowly.

A renewed interest has been given to the subject by the publication of Lord Kelvin's *Baltimore Lectures*, an entire long lecture, pages 324–407, being devoted to reflection. He remarks that very few experimenters have determined the proportion of the whole reflected to the whole incident light, and says that it is greatly to be desired that thorough investigation of this kind should be made. The present writer hopes to continue his experiments and thus contribute to this desired result.

III. METHOD OF EXPERIMENTING

The present investigation was undertaken through a suggestion made some time ago by Mr. J. R. Collins, secretary of the R. A. S. C. Mr. Collins and his brother, Mr. Z. M. Collins, designed, and in the year 1896 constructed, an achromatic telescope of 11.25 cm (4.5 inches) aperture, in which the light first passed through a double-convex objective of plate glass and then fell on a concavo-convex lens, also of plate glass, silvered on the back. Being reflected by this silvered surface, the light was returned to a small reflector, or, preferably, a total-reflecting lens-prism, near the posterior face of the objective, and thence into the eyepiece. (See Fig. 1.)

The focal length was 120 cm (48 inches), and the tube was 60 cm (24 inches) long.[2]

[1] *Phil. Trans.*, **180** A, 245, 1889.

[2] See *Trans. Astron. and Phys. Soc.*, Toronto, 1897, p. 23; *Toronto Astron. Soc.* 1900, p. 30; *Knowledge*, **23**, 252, 1900.

A somewhat similar arrangement is described by Schupmann in his work, *Die Medial-Fernrohre*, Leipzig, 1899, though all the figures in it call for two kinds of glass, crown and flint.

It was in discussing the efficiency of such a combination, involving reflection internally at a silvered glass surface, that the present investigation originated.

The method employed in it has, I believe, advantages over those previously used.

FIG. 1

A (Fig. 2) is a carriage moving on the ordinary photometric bench and bearing a Hefner standard lamp, *L*. *B* is another carriage. On this is a wooden arm *CD* which can revolve about a vertical axis through the center of the carriage. Just above this arm is a graduated brass disk *E*, rigidly fastened to the carriage. A pointer on the arm *CD* allows its position with respect to the disk to be read, and when the arm is parallel to the rails of the bench the reading is zero. A

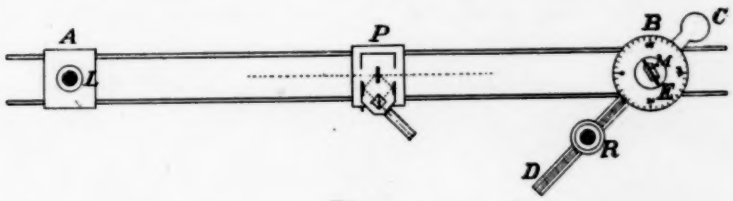

FIG. 2

second Hefner lamp *R* held in a turned wooden block can be slid along the arm *CD*, and a scale on this arm allows the distance of the axis of the lamp from the center of the graduated disk *E* to be read off directly. A small round table at the center of the disk *E* carries the mirror to be tested. This table can turn about the axis of the disk, and the mirror *M* is held between two metal strips so that the reflecting surface is at the center of the table. *P* is a Lummer-Brodhun photometer, the one used in these experiments being by Schmidt & Haensch, and arranged for equality of contrast.

It was necessary that the two lamps *R*, *L* should remain constant over an extended set of readings, and to this end cylindrical glass chimneys were placed over the flames, with a piece of fine wire gauze over the top and another over the bottom of the chimney. This

answered admirably, the flame being entirely unaffected by air currents.[1] In order to render the law of inverse squares more rigorously applicable, the glass chimneys were covered with black paper in which was made an aperture 1 cm high opposite the middle portion of the flame (Fig. 3). This flame was approximately of the height required for the standard lamp, but no attempt was made to have it accurately so, nor to have the two lamps accurately equal to each other. The only requisite was that the ratio of one to the other should remain constant. When working with a glass surface, of which the reflectivity is small, the aperture in the black paper about the left lamp had to be reduced in size. It may be remarked, too, that the photometric bench had black velvet hangings all about it, except where the observer was working.

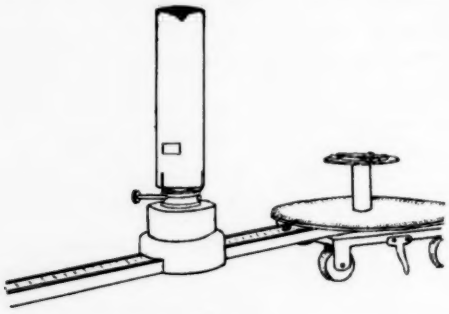

FIG. 3

The method of operation was as follows: First the arm CD was turned to zero on the disk E, and the lamps R, L turned so that the photometer was exposed to their flames, the positions of the carriages A and B and of the lamp R on the arm being carefully observed. The photometer P was then moved until equally illuminated by the two lamps, and its position noted. This adjustment was usually repeated five or six times, and the mean taken. The distances thus obtained give the ratio between the two lamps. Then the arm CD was turned through twice the desired angle of incidence, and the lamp R turned about until its aperture was toward the mirror M. P was then moved until equilibrium was obtained between the light received directly from L and that received from R by reflection at M. This adjustment was made from four to seven times, and the mean taken.

In obtaining the ratio between the two lamps, let the distances of L and R from P be a, b respectively.

Then

$$L/R=(a/b)^2.$$

[1] For this expedient, and also for some preliminary experiments, I am indebted to Miss L. B. Johnson, B.A., and Mr. W. H. Day, B.A., senior students at the time.

Again, let equilibrium be obtained when the distances from L to P, P to M, M to R are c, e, f, respectively.

Then if x be the reflectivity, we have the relation

$$x=\left(\frac{a}{b}\times\frac{e+f}{c}\right)^2\times 100 \text{ per cent.}$$

The calculations were made by this formula.

The ratio between the two lamps was found at the beginning, the end, and usually also at the middle of a series of readings.

IV. RESULTS

Table I illustrates the method. It was obtained with Mirror II*a*, plate glass silvered on the front surface. The left lamp was at 70 cm to the left of zero; the right carriage at 120 cm to the right of zero;

TABLE I

MIRROR II*a*, SILVER IN FRONT

Readings of Position of Photometer

Ratio of Lamps	Reading on Arm	ANGLE OF INCIDENCE					
		5°	10°	20°	40°	60°	80°
At Beginning	$20=f$	35.04	35.20	35.15	35.34	35.00	34.80
		35.25	35.15	35.26	35.50	35.10	35.04
14.72		35.42	35.05	35.42	35.48	35.20	34.90
14.76		35.30	35.24	35.50	35 46	35.32	34.80
14.68							
14.58	Mean	35.252	35.160	35.332	35.445	35.155	34.885
14.680	Hence $c=$	105.252	105.160	105.332	105.445	105.155	104.885
	$e=$	84.748	84.840	84.668	84.555	84.845	85.115
At End	$30=f$	40.30	40.62	40.52	40.12	40.34	39.80
		40.28	40.70	40.26	40.26	40.28	40.08
14.25		40.40	40.70	40.32	40.36	40.30	40.22
14.25		40.26	40.62	40.40	40.60	40.30	40.30
14.60							
14.28	Mean	40.310	40.660	40.375	40.335	40.305	40.100
14.345	Hence $c=$	110.310	110.660	110.375	110.335	110.305	110.100
	$e=$	79.690	79.340	79.625	79.665	79.695	79.900
		45.10	45.40	45.62	46.18	45.88	45.68
Mean, 14.5125;		45.60	45.62	45.78	45.94	45.90	45.60
and $f=20$		45.22	45.72	46.00	46.08	45.70	45.60
Hence		45.32	45.52	45.80	46.18	45.60	45.54
$a=84.5125$							
$b=85.4875$	Mean	45.310	45.565	45.800	46.095	45.770	45.605
	Hence $c=$	115.310	115.565	115.800	116.095	115.770	115.605
	$e=$	74.690	74.335	74.200	73.905	74.230	74.395

and the numbers in the table give the positions of the photometer to the right of zero. From these readings *a*, *b*, *c*, *e*, *j* are at once deduced.

TABLE II

REFLECTIVITIES OF MIRRORS FOR ANGLES OF INCIDENCE FROM 5° TO 80°

Mirror	Angle of Incidence						Remarks
	5°	10°	20°	40°	60°	80°	
I*a*. Silver before glass....	95.62	95.84	95.45	96.07	96.44	95.94	Fresh mirror
II*a*. Silver before glass....	96.71	96.13	95.99	96.57	96.32	97.08	Fresh mirror
III*a*. Silver before glass, thick film.....	95.56	95.14	94.41	94.61	94.93	95.10	Fresh mirror
Mean	95.96	95.70	95.30	95.75	95.90	96.04	
III*a*. Silver before glass....	68.39	69.34	69.66	69.17	68.11	....	3 months old
I*b*. Silver behind glass...	87.40	87.42	87.17	87.65	87.59	86.69	Fresh mirror
II*b*. Silver behind glass...	90.84	90.75	90.64	90.05	88.14	83.24	Fresh mirror
III*b*. Silver behind glass...	90.88	90.77	90.58	90.03	88.41	80.76	Fresh mirror
Mean	89.70	89.65	89.46	89.24	88.05	83.56	
III*b*. Silver behind glass...	88.19	87.35	86.35	87.33	87.35	.....	3 months old
IV. Commercial mirror...	86.75	85.99	85.62	85.69	86.16	92.39	3 years old
V. Plate glass, one face..	3.98	4.08	4.20	4.70	9.33	40.90	Plate "backed"
	4.25	4.25	4.27	4.70	9.17	39.07	Calculated
VI. Flint glass.....	5.37	5.39	5.48	6.29	10.46	40.80	
	5.59	5.59	5.62	6.23	10.82	40.40	Calculated
VII. Dense flint.....	6.82	7.02	7.11	7.79	12.40	42.21	
	7.10	7.10	7.13	7.77	12.42	41.38	Calculated
VIII. Glass plate, both faces.	7.68	7.66	7.70	8.82	15.76	59.84	Same plate as V.
IX. Silver plate.....	66.09	65.34	65.28	65.25	66.01	72.34	Inferior polish
		[70.05	70.06	70.87	74.19	81.19	Conroy]
X. Speculum metal.....	57.23	57.99	58.08	57.39	58.24	65.24	Inferior polish
		[66.13	66.88	67.26	66.32	70.17	Conroy]
		[67.26					Herschel]
		[67.52					Potter]

In Table II are given the final measurements made with the various mirrors.

I*a*, I*b*, denote the same mirror with faces reversed; similarly with II*a*, II*b*; III*a*, III*b*. These three mirrors were about 6 mm thick, and were silvered by Brashear. The following notes were made on them before testing their reflectivities:

I. Of ordinary density for a speculum, and with silvering as perfect as could be. Glass surface a little scratched, and not polished as highly as possible.

II. Not quite so dense as I, but silvering equally good. Reflected

white light rather better, i. e., without the reddish tinge due to the rouge used in polishing. Glass side polished rather better than in I.

III. Doubly silvered; film much thicker. Polish of silver surface not quite equal to the others. Showed slight rouge tint. Glass surface as in II.

The other reflectors were as follows:

IV. Commercial mirror, 2.8 mm thick, and at least three years old. Before using, its face was cleaned and rubbed with rouge on chamois.

V. Plate glass 2.8 mm thick and of refractive index 1.5193 (sodium light). Face rubbed with chamois. To avoid reflection from the posterior surface, this surface was coated thickly with the preparation used for "backing" photographic plates. This answered admirably. When a candle flame was observed in the plate not a trace of a second image could be seen.

VI. Flint glass, one face of a prism of refractive index 1.6194. The other faces were blackened.

VII. Dense flint, one face of a prism from a spectroscope by Lütz, and described as very dense white flint. The face was tarnished and had to be repolished. The refractive index was 1.7265.

VIII. Glass plate; the same as V without backing.

IX. Silver plate, of jeweler's "pure silver." The polish was not very good.

X. Speculum metal; a flat mirror by Brashear, but having become tarnished, was repolished, though not very well, as the low reflectivity indicates. The measures taken, however, show what variation in the reflectivity there is with the incidence.

The calculated results given were obtained by substituting in the Fresnel formula

$$\frac{1}{2}\left[\frac{\sin^2(i-r)}{\sin^2(i+r)}+\frac{\tan^2(i-r)}{\tan^2(i+r)}\right].$$

The results in Table II are shown graphically in the curves of Fig. 4.

It would appear from the table that with the mirrors I*b*, II*b*, III*b* (silver behind glass), the reflectivities are smaller for 60° and 80° than for the lower incidences. This anomaly is undoubtedly due to the multiple reflection within the thick plate, for which it is

impossible properly to allow. With the commercial mirror, which was not half as thick, this effect is not observable.

Though the reflectivity of silver behind glass is about 6 per cent. smaller than that of silver before glass, this disadvantage is much

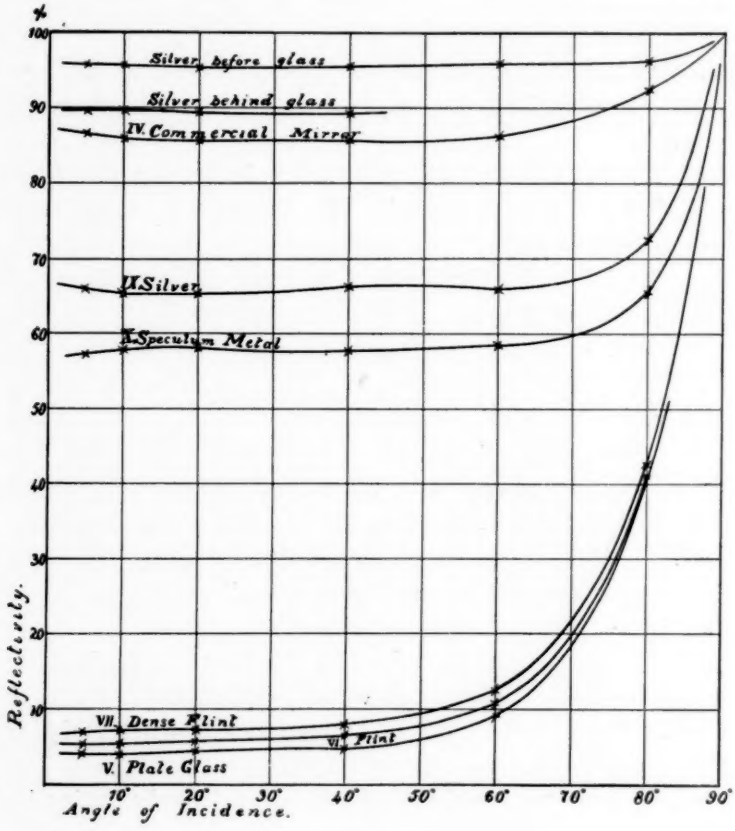

FIG. 4

more than balanced by the permanence of the former. After three months the mirror III had become so tarnished that as III*a* it fell from 96 per cent. to 68 per cent. but as III*b* it fell only from 91 per cent. to 88 per cent.; and ordinary commercial mirror at least three years old was at 86.7 per cent.

It will be interesting to determine the internal reflectivity of glass and of silver-on-glass. This may be calculated in the following way:

Let I (Fig. 5) be the intensity of light incident on a glass plate at A. A portion R is reflected and $(I-R)$ enters. Suppose that while traveling from A to B this is reduced by absorption to $(I-R)s$. If now the internal reflectivity be r, the part reflected at B is equal to $(I-R)\,sr$. By the time this reflected portion arrives at C it has been reduced by absorption to $(I-R)s^2r$. The portion of this which is reflected at C is $(I-R)\,s^2r^2$; and so on.

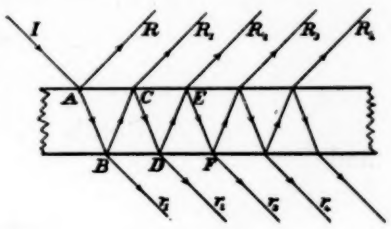

FIG. 5

Then

$$R_1=(I-R)rs^2(1-r)\,,$$
$$R_2=(I-R)r^3s^4(1-r)\,;\ \text{etc.}$$

Hence

$$R_1+R_2+R_3+\ldots\ldots=(I-R)rs^2(1-r)\,[1+r^2s^2+r^4s^4+\ldots]$$
$$=(I-R)rs^2(1-r)\frac{1}{1-r^2s^2}\,.$$

Now for a plate 2.8 mm thick

$$\left.\begin{aligned} I&=100 \ \text{per cent.},\\ R&=\ 4 \ \text{per cent.},\\ R_1+R_2+R_3\ldots&=\ 7.7 \ \text{per cent.}\end{aligned}\right\}\ \text{(see Table II)}$$

Hence

$$\frac{rs^2(1-r)}{1-r^2s^2}=\frac{3.7}{96} \qquad (1)$$

Again, Conroy found that light of mean refrangibility on traversing 1 cm of crown glass has its intensity reduced by 2.62 per cent.

Here the reduction by 1 cm of glass is from 1 to $\frac{97.38}{100}$, and the reduction by 0.28 cm of glass is from 1 to $\left(\frac{97.38}{100}\right)^{0.28}$; i. e.,

$$s=\left(\frac{97.38}{100}\right)^{0.28}=\frac{99.26}{100}\,.$$

Substituting this value of s in equation (1), and solving the quadratic in r thus obtained, we find

$$r=4.07 \ \text{per cent.},$$

the value of the internal reflectivity of glass.

For a plate silvered on the back, let p be the internal reflectivity for silver-glass. Then, as before,

$$R_1=(I-R)s^2p(1-r),$$
$$R_2=(I-R)s^4p^2r(1-r),$$
$$R_3=(I-R)s^6p^{3,2}(1-r), \text{ etc.}$$
$$R_1+R_2+R_3+\ldots\ldots=(I-R)(1-r)s^2p(1+s^2pr+s^4p^2r^2+\ldots\ldots)$$
$$=(I-R)(1-r)s^2p\frac{1}{1-s^2pr}\ .$$

Now

$$R+R_1+R_2+R_3+\ldots=90 \text{ per cent.}$$
$$R=\ 4 \text{ per cent.}\Big\} \text{(Table I),}$$

and

hence

$$\frac{(1-r)s^2p}{1-s^2pr}=\frac{86}{96}\ . \qquad (2)$$

Using the values deduced above, namely,

$$s=\frac{99.26}{100}\ , \qquad r=\frac{4.07}{100}\ ,$$

we find

$$p=0.913, \text{ or } 91.3 \text{ per cent.}$$

i. e., the internal reflectivity of silver-glass is 91.3 per cent.

A formula similar to that for the reflected light can be found for the portion transmitted through a glass plate,

$$r_1+r_2+r_3+\ldots\ldots=(I-R)s(1-r)(1+r^2s^2+r^4s^4+\ldots\ldots)$$
$$=(I-R)s(1-r)\frac{1}{1-r^2s^2}\ ,$$

and on substituting in this expression the values for r and s determined above, we find

Transmitted light=91.5 per cent.

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Toronto, Canada.

SPECTRA FROM THE WEHNELT INTERRUPTER[1] II

By HARRY W. MORSE

In a previous paper under the same title[1] there were reported measurements of the spectra of a number of metals used as active points in an arrangement similar to the Wehnelt interrupter. Tables of wave-lengths and intensities were given, and comparison tables for the arc and condensed spark of the metal in each case.

The present paper contains: (1) Similar measurements on the spectra of copper, gold, cadmium, iron, palladium, and platinum, photographed under the same conditions as have been described in the previous paper. The measurements for iron and platinum are from the third-order spectrum, the others from the first-order spectrum of the grating employed. (2) A brief qualitative note on the spectra which contain lines of both the point used and the metal in solution. (3) A note of the bands found in the Wehnelt and their occurrence in the spectra of the same metals under other conditions. (4) General comparisons of certain lines from the spectra of this and the previous paper with the same lines produced under special experimental conditions, as, e. g., in the spark with inductance, in the arc in hydrogen, etc.

The examination of the more complex spectra has not led to so much of interest as has been found in the simpler ones. It has, however, seemed best to publish tables of at least a part of the lines, in the hope that further knowledge of these spectra may increase their value.

The large number of lines in the Wehnelt spectrum, compared with that in the ordinary condensed spark between copper terminals, is remarkable. Not only are all the lines usually found in the spark spectrum present, but also most of those found by Eder and Valenta by means of a very strong condensed transformer spark. Among lines especially remarkable in this way are λλ 3530.5, 4063.0, 4275.0 and 4509.5. These are lines produced when the energy of the spark is

[1] *Astrophysical Journal*, **19**, 162, 1904.

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(Fig. 1)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3247.5	20 (10)	5	20	4378.5	— (1)	4	—
3274.0	20 (8)	20	30	4480.4	— (3)	4	3
3308.0	3 (7)	3	1	4509.5	— (4)	—	4
3337.5	— (4)	—	1	4531.0	— (2)	—	4
3416.0	— (1)	4	—	4587.0	— (8)	6	1
3530.5	— (3)	—	3	4651.5	2 (8)	8	50
3571.8	— (—)	—	1	4675.0	— (6)	3	—
3599.5	— (1)	—	5	4704.6	— (5)	—	5
3654.5	— (1)	3	—	4933.5	3 (4)	—	—
3685.0	2 (3)	—	—	5105.5	6 (8)	30	100
3688.5	— (—)	5	—	5153.5	5 (10)	25	30
3839.0	— (2)	—	1	5218.5	20 (10)	15	100
3860.8	— (2)	—	1	5293.0	3 (6)	2	4
4023.0	1 (4)	8	5	5454.1	— (1)	—	1
4063.0	— (7)	8	6	5536.0	15 (3)	20	—
4080.5	— (—)	8	—	5700.5	3 (6)	15	20
4249.5	— (3)	—	1	5782.2	5 (8)	20	50
4275.2	— (10)	6	20				

Spark—Between copper points.

Arc—Metal on carbon terminals.

Wehnelt—Copper wire in dilute hydrochloric acid.

The intensities in brackets are those of Eder and Valenta,[1] obtained with a heavy transformer discharge. They are given on a scale of 1 to 10.

great and the temperature apparently very high. King[2] states that very little difference was noticeable between the spectra from sparks of very different intensities under the conditions of his experiments. I do not find these spark lines in measurable intensity on any of my plates. A few lines belonging to the arc spectrum are not present in the Wehnelt in sufficient strength to be observed. Among these are λλ 3688.5, 4080.5. Aside from these, there are a number of lines present in both arc and spark, which are absent from the Wehnelt table. λλ 3416, 3654, 4675, 5536, are of this kind. The last is a very strong line in both spark and arc.

The lines of copper for which Kayser and Runge have found series relation of a simple sort are:

[1] *Wien. Akad. Denkschriften*, 1896.

[2] *Astrophysical Journal*, **20**, 21, 1904.

5218.5*d*, 5153.5 } Stronger in Wehnelt than in spark or arc.
4063.0*d*, 4023.0 } Stronger than in the spark. Weaker than in arc.
3688.5, 3654.5 } Absent from Wehnelt.
3274.5, 3247.0 } Strong in all three spectra.

(The doublets marked *d* are not resolved by the dispersion employed.)

These lines are evidently not proportionately affected by the change of experimental conditions.

A large proportion of the lines which are especially strong in the Wehnelt spectrum are lines usually characteristic of low temperatures. The lines λ 5218.5 and λ 5105.0 are strong in the flame spectrum, and a number of the other strong lines are characteristically strong in the spectrum of the spark passing to solutions of copper salts. It is especially remarkable in this connection that nearly all of the lines of the high-temperature transformer spark are also present and strong.

GOLD
(Fig. 2)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3554.0	3	5	1	4315.5	5	—	10
3572.0	—	—	1	4364.5	—	6	—
3586.5	5	—	4	4437.0	3	4	5
3651.0	1	—	1	4488.5	4	4	10
3750.5	—	—	2	4608.0	3	3?	5
3795.8	1	—	2*b*?	4792.5	25	30	100
3874.5	—	—	1	4811.5	5	4?	5
3898.0	10	5	30	4861.0*b*?	—	—	2
3909.5	2	3	1	5064.5	5	5	3
b	..	..	band	5230.0	15	4	8
4016.0	5	—	1	5465.8	1	—	3
4041.0	..	5	3	5581.0	5	—	1
4053.0	3	—	—	5611.0	—	—	1
4065.5	15	10	30	5656.0	6	4	5
4084.5	2	5	2	5837.5	6	3	8
4242.0	2	5	2	5863.0	3	4	1

Spark—Between gold terminals.
Arc—Metal on carbon terminals.
Wehnelt—Gold wire in dilute hydrochloric acid.
The lines of impurities are those of lead and silver.

This spectrum of gold differs markedly from both the spark and the arc spectrum of the metal in the far greater number of its strong

lines and the corresponding contrast as compared with the rather weak, flat spectra characteristic of the other experimental conditions. Several new lines are noted, and distinct traces of an underlying band spectrum are visible. The lines at λλ 3898.0, 4065.5, and 4792.5 are very much stronger than any lines obtainable in arc or spark. Several spark lines are enhanced, and the lines λλ 4016.0 and 5581.0, and some others, are reduced. The Wehnelt spectrum is in many parts very like that of the spark, and not in the least like that of the arc, which contains only about half as many lines in intensity sufficient to be observable. Some of the lines on the Wehnelt are characteristic of the spark in its strongest and most condensed form.

A band of considerable strength runs from λ 3910.0 to λ 4016.0, and a weaker band is visible with head at λ 4861.0 in the Wehnelt spectrum.

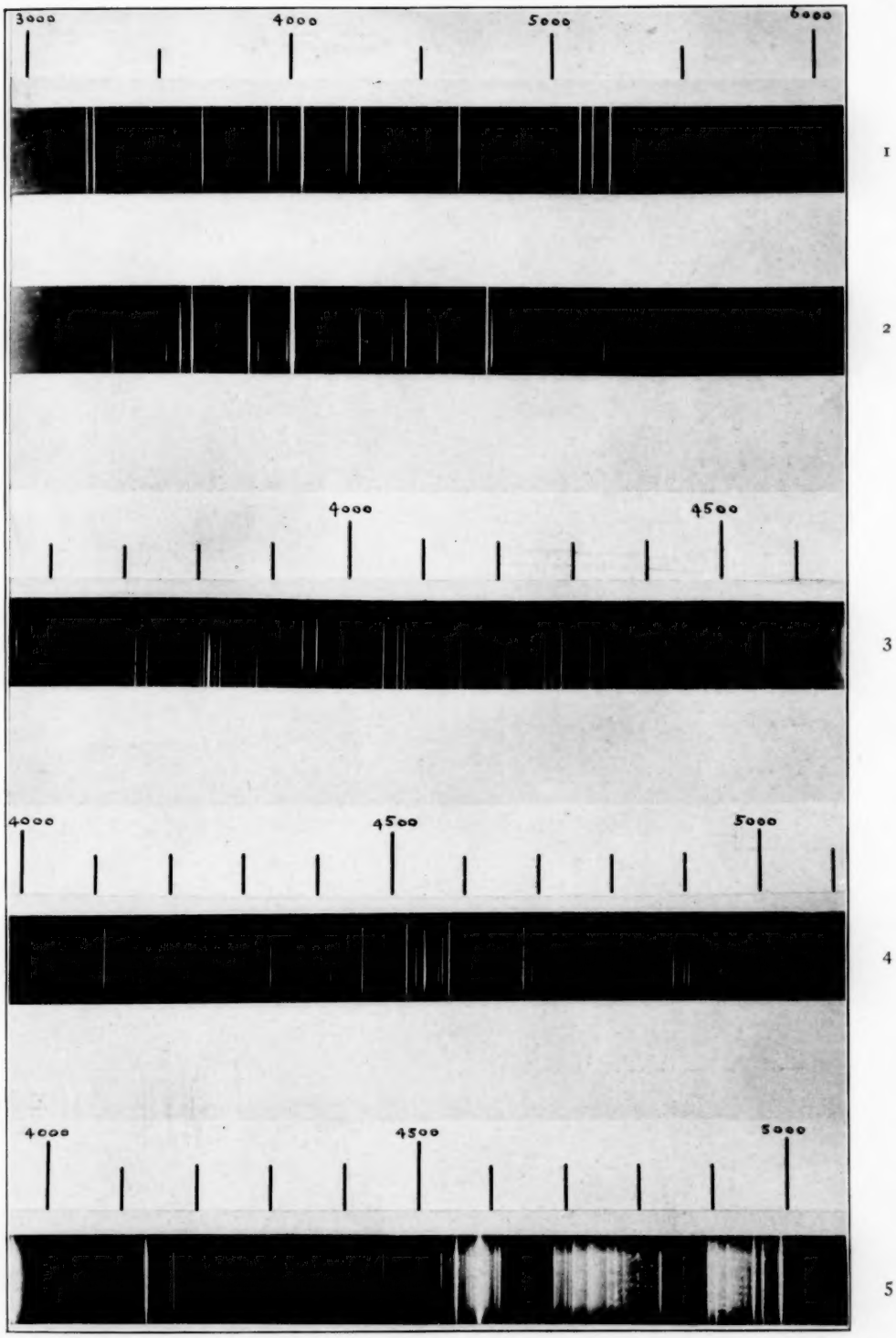
CADMIUM

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3250.5	10	15	3	4313.0	—	—	1
3261.0	25	20	8	4416.0	20	—	3
3403.5	30	20	25	4491.0	—	—	1
3467.0	50	30	40	4510.5	—	—	1
3610.5	50	30	50	4664.0	—	4	1
3734.0	—	—	1	4678.5	25	40	40
3776.5	—	—	1	4800.0	30	40	40
3822.5	—	—	1	5086.0	30	50	40
4102.0	—	—	1	5155.0	—	—	1
4122.5	—	—	1	5338.0	50*f*	—	3
4176.5	—	—	1	5348.5	—	—	1
4297.0	—	—	1	5379.0	50*f*	—	4

Spark—Between cadmium terminals.
Arc—Metal on carbon terminals.
Wehnelt—Cadmium wire in dilute hydrochloric acid.

The Wehnelt spectrum of cadmium is in many respects like those of zinc, tin, and lead. The pair of lines at λλ 5338.0 and 5379.0 belongs to the class already referred to under these metals as being strong, broad, and diffuse in the spark, absent from the arc, and sharpened and reduced in intensity in the Wehnelt. The line λ 4416.0 has these same peculiarities, while λλ 3250.5 and 3261.0 are present with nearly equal intensity in arc and spark, and are much reduced in the Wehnelt.

PLATE XIII



SPECTRA FROM WEHNELT INTERRUPTER

1. Copper point in hydrochloric acid. 2. Gold point in hydrochloric acid. 3. Iron point in hydrochloric acid (3d order spectrum). 4. Platinum point in hydrochloric acid (3d order). 5. Aluminum point in barium chloride solution (3d order).

IRON

(Plate XIII, Fig. 3)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3872.6	4	8	6	4198.6*d*	6	10	12
3878.5	4	8	8	4202.2	6	10	10
3885.6	5	6	8	4210.3	3	5	3
3887.8	4	6	6	4219.4	3	5	4
3894.9	3	5	5	4222.3	2	5	2
3899.0	4	6	5	4224.2	1	3	1
3902.3	5	8	6	4225.5	1	4	1
3905.7	4	6	1	4227.6	3	10	8
3917.9	—	6	1	4233.7	3	10	7
3919.4	4	6	4	4236.0	4	10	10
3922.1	4	8	4	4238.8	2	5	2
3928.1	4	8	6	4245.4	1	4	1
3930.3	4	8	6	4247.5	2	5	3
3933.5	—	6	1	4250.8*d*	6	10	10
3956.7	3	6	2	4260.6	12	10	8
3966.5	3	5	2	4271.8	12	10	12
3969.4	6	8	10	4282.5	4	8	5
3973.2	—	4	1	4294.2	4	8	6
3977.7	3	7	1	4299.4	4	8	7
3997.6	3	6	3	4307.9*d*	15	10	12
4005.4	6	7	10	4315.2	3	10	5
4009.7	2	5	1	4326.0*t*	15	10	15
4014.2	2	5	1	4336.9	3	8	4
4021.9	2	5	2	4352.9	2	5	4
4030.9	—	5	10	4367.4	1	4	1
4033.2	—	5	8	4369.8	2	5	2
4034.5	—	5	7	4375.9	2	5	2
4041.3	—	5	5	4383.9	15	15	15
4045.8	15	15	30	4387.9	1	4	2
4055.4	—	5	1	4404.8	12	15	15
4063.7	10	20	30	4408.2*d*	2	4	2
4071.9	8	20	25	4415.2	10	10	12
4076.5	—	6	1	4422.3	1	5	2
4079.7	—	6	1	4427.3	2	5	2
4083.4	—	5	1	4430.3*d*	1	5	2
4084.8	—	6	1	4442.4	2	5	6
4107.4	2	6	2	4447.7	2	8	5
4109.8	2	8	2	4451.5	—	2	4
4118.7	3	10	5	4454.4	1	3	1
4127.6	—	5	1	4458.0	2	—	5
4132.2	5	10	10	4461.8	1	4	2
4134.6	2	10	5	4466.6	2	6	5
4144.0*d*	6	10	10	4469.3	2	4	2
4154.5	3	5	3	4476.0	2	8	6
4156.8	3	6	2	4482.2	3	4	5
4175.5	2	6	2	4494.6	2	4	8
4181.9	4	8	8	4528.8	3	6	10
4184.9	2	8	2	4547.9	—	4	2
4187.8*d*	4	10	10	4555.6	—	4	—
4191.5	3	10	4				

Spark—In air between iron points.

Arc—Metal on carbon terminals.

Wehnelt—Iron wire in dilute hydrochloric acid.

Wave-lengths of a number of weak lines are given in the Wehnelt column without note as to whether they are lines or maxima of bands. The position and general character of these maxima lead me to

PALLADIUM

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3243.0	10	20	20	4343.5	—	2	2
3251.5	6	10	25	4385.0	—	1	2
3259.0	8	10	10	4407.0	1	3	2
3267.5	6	5	8	4421.5	—	1	1
3279.0	—	—	8	4443.0	—	2	1
3287.5	3	5	5	4473.5	5	10	40
3302.5	15	15	40	4489.5	1	4	2
3373.0	10	15	25	4516.5	1	4	2
3383.0	1	10	10	4541.0	1	4	2
3405.0	30	20	50	4590.5	—	2	1
3421.5	15	10	8	4631.0	—	1	1
3430.0	1	2	5	4651.0	—	—	1
3433.5	10	10	10	4677.0	—	2	1
3441.5	10	10	8	4722.0	—	1	2
3446.0	—	—	8	4787.5	10	10	15
3451.5	10	—	—	4817.0	10	10	20
3461.0	15	10	15	4875.0	10	10	10
3481.5	20	10	20	4920.5	—	2	2
3490.0	10	10	15	4970.5	—	2	2
3517.0	20	10	20	5062.0	4	2	1
3553.0	30	8	20	5110.5d	10	5	5
3571.5	10	10	5	5163.0	15	10	15
3610.0	30	10	10	5209.0	5	3	1
3635.0	30	10	5	5215.0	—	—	1
3691.0	10	10	10	5234.0	10	8	3
3719.0	10	8	8	5256.0	5	2	1
3739.0	5	—	1	5294.0	15	10	20
3799.5	10	8	20	5309.5	5	2	1
3832.5	10	—	15	5342.0	5	2	1
3859.0	—	—	1	5361.5	5	2	2
3894.5	15	8	25	5394.0	10	2	6
3958.5	10	8	25	5431.5	—	—	1
4021.0	—	1	2	5462.5	—	—	1
4045.0	—	—	1	5495.0	—	—	1
4058.0	2	—	3	5524.0	—	—	1
4087.5	5	8	15	5542.0	10	10	50
4099.0	—	1	2	5589.5	—	—	3
4124.0	1	2	1	5606.5	1	4	4
4170.0	5	4	5	5629.0	—	2	2
4213.0	20	10	40	5640.0	5	3	1
4224.5	—	—	1	5668.5	8	10	30
4268.0	—	2	2	5694.0	8	8	15
4302.5	—	—	1	5736.5	5	5	5
4325.0	—	—	1				

Spark—Between palladium terminals.

Arc—Metal on carbon terminals.

Wehnelt—Palladium wire in dilute hydrochloric acid.

believe that they are bands similar to those found by Jones[1] in the spectrum of the vapor of cadmium in Geissler tubes. There are traces of a band from λ 4416.0 to λ 4491.0, and of another from λ 4297.0 to λ 4102.0, which correspond to bands found by Jones.

The plate shows the above region, photographed in the third-order spectrum. An aluminium spark was used merely to furnish a few lines for a starting-point in the measurements. The aluminium and air lines are visible, coming part way across the plate.

The Wehnelt spectrum of iron contains nearly all of the arc lines, many of them with greatly reduced intensities, and the whole appearance of the spectrum is like that of the arc, all of the lines being perfectly sharp and clear.

The groups λ 4030.9−λ 4041.3, and λ 4076.5−λ4084.8, show how the spectrum resembles that of the arc, reduced in intensity. In other parts strong spark lines appear enhanced in the Wehnelt, but nowhere is it exactly similar to either of the other spectra over any considerable range.

The spectrum of palladium is an especially interesting one on account of its many strong lines, but there are no very marked differences between arc, spark, and Wehnelt spectra. Measurable differences of intensity occur everywhere, and there are a considerable number of lines which are strong in the spark, weaker in the arc, and weaker still in the Wehnelt. Examples are λλ 3635.0, 3739.0, 5256.0, 5309.0, and 5342.0. Occasionally a weak spark line appears enhanced in the Wehnelt, as λλ 3251.5, 3383.0, and 4473.5. I have been unable to find any relation between the appearance of the lines of palladium and their intensities in the different spectra. A considerable number of the lines of the spark spectrum are diffuse, and there are others which are diffuse in the arc. All of these are sharp in the Wehnelt.

The lines given for platinum are from a photograph in the third-order spectrum. There are many small differences of intensity, but none marked enough to offer any clue to the relation between spectra. All of the lines in the Wehnelt spectrum are perfectly sharp. There is no sign of a banded spectrum.

[1] *Wied. Ann.*, **62**, 30, 1897.

PLATINUM

(Plate XIII, Fig. 4)

Wave-Length	Spark	Arc	Wehnelt	Wave-Length	Spark	Arc	Wehnelt
3900.7	5	5	8	4309.3	1	—	2
3904.3	1	2	3	4327.3	4	10	8
3911.0	3	2	2	4334.9	2	3	3
3923.2	15	3	15	4347.0	—	7	4
3948.6	3	6	2	4358.5	3	3	4
3966.6	7	12	10	4370.5	—	10	..
3996.7	3	—	2	4379.0	—	8	..
4066.5	—	3	3	4392.1	5	10	8
4081.7	3	2	4	4411.7	1	4	4
4092.5	3	3	4	4414.6	1	3	2
4119.0	10	10	15	4437.5	3	5	7
4164.8	7	6	10	4442.8	6	8	10
4192.7	6	6	10	4445.7	1	5	2
4201.3	1	2	2	4458.8	1	4	4
4227.5	1	4	..	4473.6	1	6	4
4251.2	1	1	1	4484.8	1	8	8
4260.2	1	—	1	4499.0	10	6	15
4263.8	1	2	2	4521.1	3	6	10
4288.2	2	5	2	4523.2	2	6	8
4291.0	1	2	1	4548.2	3	4	6
4302.6	2	—	3	4552.7	8	6	10

Spark—Between platinum terminals.

Arc—Metal on carbon terminals.

Wehnelt—Platinum wire in dilute hydrochloric acid.

II

It may be of interest to record the types of spectra produced when both the metal of the active point and the metal in solution in the electrolyte show lines. I shall give data for platinum, as that metal has been used under more varied conditions than any other. Qualitatively the results are as follows:

Platinum point in—

Hydrochloric acid	Only platinum lines
Sulphuric acid	Only platinum lines
Nitric-acid	Only platinum lines
Boric acid solution	Only platinum lines
Ammonium nitrate solution	Only platinum lines
Ammonium chloride solution	Only platinum lines
Lithium chloride solution	Platinum and lithium lines both strong
Potassium carbonate solution	Platinum and potassium lines both strong
Potassium chloride solution	Platinum and potassium lines both strong
Calcium chloride solution	Platinum lines weak; calcium lines strong

Strontium chloride solution	Platinum lines weak; strontium lines strong
Barium chloride solution	Barium lines only
Aluminium nitrate solution	Lines of both platinum and aluminium about equally strong
Mercuric nitrate solution	Platinum lines weak; mercury lines strong
Zinc chloride solution	Platinum lines quite strong; zinc lines strong
Zinc bromide solution	Platinum lines quite strong; zinc lines strong
Manganese sulphate solution	Platinum lines weak; manganese lines strong

Aluminium, when used as active electrode in almost any salt solution, shows its lines strongly (see Fig. 5). The plate chosen shows how the lines of the point and those of the metal in solution combine into a composite spectrum, without their relative intensities being in any way changed.

As has been stated in the first paper of this title, the condition favorable to the "Zerstäubung" of a platinum point and that favorable to a bright luminescence differ only slightly. It is evident that the point is furnishing glowing metallic vapor while the action is going on, and that the spectrum from this may, under some circumstances, be as strong as that from the metal left as vapor by the evaporation and dissociation of the water of the solution. Where the metal of the point is volatile only at a very high temperature (e. g., platinum) it might be expected that the spectrum of the released metal from the kation would predominate. In many cases, however, the platinum lines are as strong as those from the dissolved substance.

III

The metals which show especially remarkable bands in their Wehnelt spectra are zinc, tin, cadmium, and gold. On working over the literature of these metals with greater care, it seems evident that the bands noted for all of these except gold have been previously observed under special experimental conditions.

Zinc.—Bands of zinc were measured by Jones,[1] who gives maxima at λλ 4302.0, 4260.0, and 4240.0, tailing off toward the violet. The approximate wave-lengths of the maxima in the Wehnelt spectrum were given as λλ 4299.0, 4257.0, and 4238.0, and it seems probable that the bands are the same. Professor A. Fowler has kindly called my attention to his measurements of bands produced in the zinc arc

[1] *Wied. Ann.*, **62**, 30, 1897.

at very low pressures,[1] and here also it seems evident that the structure is the same.

Tin.—The reproduction given by Basquin[2] of the spectrum of the tin arc in hydrogen shows lines which closely coincide with the maxima given under this metal in the previous paper on the Wehnelt. The following lines are clearly visible in the reproduction:

	Spark	Arc	Wehnelt
4512.....	absent	absent	present
4525.....	present	present	present
4585.....	present	present	present
4617.....	absent	absent	present
4720.....	absent	absent	present
4810.	absent	absent	present

The line at λ 4058 is apparently a lead line.

The lines λλ 4512, 4617, 4720, 4810 are evidently new lines of tin which appear under these conditions, although Basquin seems not to have recognized them as such. The Wehnelt spectrum contains, besides these maxima, which are evidently sharp lines, a considerable banded spectra in the violet.

Cadmium.—As has already been stated, Jones found the bands at λλ 4415.0–4494.0 and λλ 3990.0–4299.0 in the spectrum of cadmium vapor in Geissler tubes. The heads of these bands appear to be present on my own plates of cadmium in the Wehnelt, but as very weak maxima.

IV

The following table contains qualitative remarks on the intensity and appearance of certain lines under the following conditions:

1. Condensed spark.
2. Arc; metal on carbon electrodes.
3. Condensed spark with self-inductance in the secondary circuit.
4. Metal as point in the Wehnelt arrangement. (In the case of mercury the data are for a platinum point in a solution of a mercury salt.)
5. Arc under water
6. Arc in hydrogen.
7. Arc between metallic terminals.
8. Data from Schenck's analysis of the spark.

[1] *Proc. R. S.*, **72**, 253, 1903. [2] *Astrophysical Journal*, **14**, 1, 1901.

Data for the table have been taken from the papers of the following:

Inductance: Hemsalech, *Journal de Physique*, **8**, 653, 1899.
Inductance: King, *Astrophysical Journal*, **19**, 225, 1904.
Hydrogen: Crew, *ibid.*, **12**, 167, 1900.
Hydrogen: Basquin, *ibid.*, **14**, 1, 1901.
Various gases: Porter, *ibid.*, **15**, 274, 1902.
Under water: Hartmann and Eberhard, *ibid.*, **17**, 229, 1903.
Arc: metallic terminals: Hartmann, *ibid.*, **17**, 270, 1903.
Mercury: Huff, *ibid.*, **12**, 103, 1900.
Analysis of spark: Schenck, *ibid.*, **14**, 115, 1901.

Data for some of the lines under some conditions are lacking. These spaces have been left blank in the table. Where a line is absent from a spectrum the fact is noted by the word "absent."

Metal Line	1 Spark	2 Arc	3 Spark with Inductance	4 Wehnelt	5 Arc under Water	6 Arc in Hydrogen	7 Arc Between Metal Points	8 Schenck's Group
Magnesium—								
4481.0	str.[1] diff.	abs.	red'c'd sharp	red'c'd sharp	str. sharp	enh.	pres.	"B"
Zinc—								
4911.5	str.	abs.	red'c'd	red'c'd	str.		pres.	"B"
4924.0	diff.							
4058.0	abs.	str.	enh.	enh.				
Cadmium—								
4416.0	str.		red'c'd	red'c'd	str.			"B"
4678.0	str.	str.		str.				"A"
5339.0	str.	abs.	red'c'd	red'c'd	str.			"B"
5379.0	diff.		sharp	sharp	sharp			
Tin—								
3351.0	str.	abs.		red'c'd		enh.		
3282.0	diff.			sharp				
Lead—								
4062.0	abs.	str.	enh.	red'c'd				
4168.0	diff.	pres.	enh.	red'c'd				
4245.0	diff.	abs.	red'c'd	red'c'd			pres.	
4387.0	diff.	abs.	red'c'd	red'c'd				
5373.0	diff.	abs.	red'c'd	red c'd				
5547.0	diff.	abs.	red'c'd	red'c'd				
5608.0	diff.	abs.	red'c'd	red'c'd				
Mercury—								
3663.0	pres.	pres.	enh.	enh.				
3665.0	pres.	pres.	enh.	enh.				
4078.0	pres.	pres.	enh.	enh.				
4916.0	pres.	pres.	enh.	enh.				
5426.0	pres.	abs.	red'c'd	red'c'd				

As will be clearly seen in the table, the Wehnelt spectrum (with a few exceptions, as *Pb* λλ 4062.0 and 4168.0) is very much like the

[1] Str. = strong, diff. = diffuse, abs. = absent, pres. = present, enh. = enhanced.

spark spectrum with inductance in the secondary circuit. The strong diffuse lines of the spark are reduced and sharpened by the introduction of inductance, and the same effect is a general one in the same lines in the Wehnelt. The zinc line λ 4058.0, which is absent from, or very weak in, the spark, is greatly enhanced by inductance and is a strong line in the Wehnelt. In the spectrum of mercury the changes in intensity from spark to spark with inductance and those from spark to Wehnelt are closely parallel.

Several other metals not given in the table show similar changes. The aluminium lines λλ 3613.0 and 3602.0 are cut out from the spark spectrum by the addition of inductance, and they are also greatly reduced in the Wehnelt. The silver lines λλ 4668.5 and 4055.5 are enhanced by inductance and stronger in the Wehnelt than in the spark, and many other lines follow the same course of changes.

All of the lines which show striking changes in appearance and intensity under the various experimental conditions are *non-series* lines, and most of them belong to Schenck's class B, of which magnesium λ 4481.0 may be taken as a prototype. These are the lines which are, as a rule, reduced or cut out of the spark spectrum by the addition of inductance, and they are usually the lines which are enhanced in hydrogen or under water. To this class belong lines which are usually ascribed to the spark, but which appear in the arc between metallic electrodes when the current is made as small as possible.

These have been often called "high-temperature lines," but there seems to be no reason for assuming that the arc in hydrogen or under water is higher in temperature than that in air, nor is there any direct evidence that the introduction of inductance into the secondary discharge circuit decreases the actual temperature of the metallic vapor in the spark. Further analyses of the spark and Wehnelt discharges, by methods similar to those employed by Schuster and Hemsalech,[1] and Schenck,[2] should throw light on these important questions.

CONCLUSION

1. The spectra produced in an arrangement similar to the Wehnelt interrupter show well-marked differences from those belonging to the same metals as produced in the spark and the arc, both in the relative

[1] *Phil. Trans.*, 193, 189. [2] *Loc. cit.*

intensity of lines and in their appearance, but no definite *type* of spectrum appears to be characteristic of this method of spectrum production.

2. The variations in intensity between lines in spark spectra and the same lines in the Wehnelt are closely parallel to the variations from spark to spark with inductance.

3. Lines belonging to the series of Kayser and Runge show little change in appearance or intensity under varying experimental conditions. This statement, which has been proved for other cases, may now be extended to include spectra produced in the Wehnelt interrupter.

4. Non-series lines show in many cases great variations in intensity and appearance under various conditions of spectrum production.

5. The evidence that the lines which show marked variations in intensity and appearance under various conditions are those corresponding to the highest temperature seems to be by no means conclusive.

6. The bands found in the Wehnelt spectra appear also under other experimental conditions, either in the arc in hydrogen, in the arc at very low pressures, or in the Geissler tube spectrum of the metal.

My especial thanks are due to Professor Langley for the loan of the large-aperture grating used in this work. Only by its use was it possible to photograph the normal spectra of these weak luminescences with exposures of reasonable length.

JEFFERSON PHYSICAL LABORATORY,
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January 30, 1905.

SOME EMISSION SPECTRA OF METALS AS GIVEN BY AN ELECTRIC OVEN

By A. S. KING [1]

Spectroscopic investigations with the electric arc and spark have furnished much evidence that when the current thus passes through the incandescent vapor, the vibrations producing spectral lines are strongly influenced by the electrical conditions then prevailing in the arc or spark. Thus in the spark spectra of many elements there are lines which never appear in the arc spectrum, and which a closer examination shows to be easily altered in intensity by slight changes in the spark discharge. Also in the arc many variations in the spectrum seem most probably due to differences in arc conditions. Concerning the actual nature of these electrical influences our knowledge has advanced but little; crucial tests seeming in many cases impossible, since the change of one condition directly affects numerous other conditions to an unknown extent.

Clearly the production of emission spectra with electrical action excluded would be most desirable; but a temperature must be produced not far below that of the arc, unless we are to be content with a few lines, such as are given in flame spectra. Attempts to produce spectra in tubes tested in furnaces were made by several early investigators, but the first really effective method seems to have been that used by Liveing and Dewar[2] in the course of their experiments on reversibility of lines, but which they found capable of producing numerous emission lines. The essential principle of this oven has been used by the writer in the work to be described. An arc is formed between a vertical carbon rod and a horizontal carbon bored out and containing the metal to be vaporized. The carbon tube becomes very hot just above the arc, and the spectrum of the vapor appears. The observations and photographs made by Liveing and Dewar showed the efficiency of the method, but, aside from a very few observations made by them, no use seems to have been made of the prin-

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[2] *Proc. R. S.*, **34**, 119, 1882.

ciple, and it certainly has not become a recognized working method in the attempt to bridge the gap between flame and arc.

The next work along this line was concerned largely with the question whether spectra can be produced by high temperature alone. This work, beginning with E. Pringsheim's[1] experiment with sodium in a heated porcelain tube, and followed by experiments by Paschen,[2] is reviewed at length by Kayser.[3] The difficult question as to the exclusion of all chemical action which might produce luminescence is the chief contention in these articles. The temperatures used were low compared to that of the arc.

With the subject in this stage, I took up the problem, at the suggestion of Professor Kayser, of developing a method for producing emission spectra in a tube heated by electricity as nearly as possible through the agency of heat alone. When a practical oven had been devised, the work of which the results are to be given was carried forward with the apparatus in its original crude form, leaving improvements in the oven for a second series of experiments.

When these results were almost ready for publication, a work by R. Nasini and F. Anderlini[4] appeared, which has the same general purpose as mine and was performed with an electric oven. Their apparatus is not sufficiently described to enable one to see whether it is at all similar to mine. Their chief experiment was the vaporization of magnesium in a graphite tube for the purpose of using up the oxygen of the air, and they thought that they observed the spectrum of nitrogen (?) under these conditions. My results for *Mg*, which is the only experiment parallel to theirs, will be given later.

APPARATUS

In the experiments to be described, two forms of oven were used; but as almost all the results so far have been obtained with one form, a description of this will be given first. It was a modification of the oven used by Liveing and Dewar, and the materials used were of the simplest sort. The figure gives a cross-section showing the arrange-

[1] *Wied. Ann.*, **45**, 428–459, 1892.

[2] *Ibid.*, **50**, 409–443, 1893; **51**, 1–39, 1894; **52**, 209–237, 1894.

[3] *Handbuch der Spectroscopie*, II, 150–157.

[4] *Rendic. Accad. dei Lincei*, (5) **13**, 59–66, 1904.

ment. Two carbon battery elements *b*, *b* were taken and a side of each hollowed out, so that, when placed together a cylindrical space about 2½ cm in diameter was formed. An ordinary cored electric light carbon *c*, 16 mm in diameter, was bored out with a hole 5 mm in diameter, placed inside the cylinder formed by the two carbon blocks, and insulated from these by two tubes of abestos *a*, *a*, each reaching about 5 cm in from the end, thus leaving the middle part of the bored-out carbon free. In the middle of the lower carbon block a hole was bored, through which a carbon *d*, 12 mm in diameter was passed. Copper clamps on the ends of both horizontal and vertical

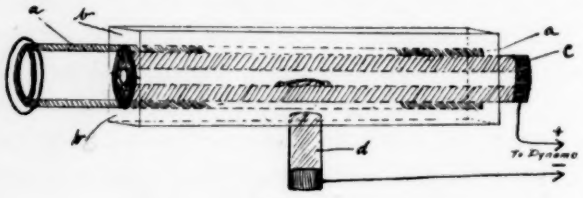


FIG. 1.

carbons connected with mercury cups, and in these were placed the terminals of a 220-volt dynamo circuit, the positive terminal to the horizontal carbon. Raising the vertical carbon then formed an arc between its end and the side of the horizontal carbon tube. With this voltage an arc of only 2 or 3 amperes could be used at first and increased slowly, as too rapid heating was liable to crack the carbon tube. This forms the essential part of the apparatus, but it was further protected by other battery carbons built up around it, which served to retain the heat and prevent oxidation of the two carbon blocks inclosing the tube, as these soon became red-hot.

This very simply constructed oven proved remarkably durable and effective. An arc of 30 amperes could be easily maintained, and the oven could be used daily for a month without any of the carbon blocks being renewed. The bored-out carbon, being the + terminal, became intensely hot, and in time would burn through, though maximum current could generally be used for half an hour and 15 to 20 amperes for a much longer time. The metal or salt whose spectrum was desired was placed in the tube directly over the arc, and further supplies could be pushed in by means of a small carbon

rod, while the spectrum was observed visually or photographed through the other end of the tube. Unless opaque vapors were given off in such quantities as to require an outlet, the tube could be made almost air-tight by letting the asbestos insulation at one end form an extension tube closed by a quartz window, while at the other end an asbestos plug was inserted in the carbon tube.

We have then an apparatus in which the substance to be vaporized is within the positive terminal of a very strong arc and separated not more than 5 mm from the arc itself. The inside of the tube becomes white-hot over a length of perhaps 5 cm, and strong emission spectra were readily obtained, from the carbon itself and metallic impurities as well as from a number of metals and salts placed in the tube directly above the arc.

After a few preliminary visual observations, the spectra thus given were studied entirely by photography, at first with a prism spectrograph in which the small glass prism used gave low dispersion, but very bright spectra; and later in as many cases as possible the spectra were photographed with a Rowland concave grating of 1 m radius, this requiring, however, much longer exposure. The narrowness of the carbon tube caused some continuous spectrum from the white-hot walls to appear, but the shortness of the incandescent portion made this continuous ground so weak as to give little trouble, even weak spectral lines appearing distinctly; and in order to eliminate the continuous spectrum as far as possible, a sharp image at the interior of the oven was projected by a quartz lens on the slit—an image so large that the ring formed by the incandescent walls did not appear on the slit. The spectrum lost somewhat in intensity thereby, but the continuous ground was rendered very weak, especially in the grating photographs.

For identification of lines and comparison with the arc lines, an arc spectrum was in most cases photographed beside the oven spectrum by placing an arc containing the metal behind the oven when the latter was not in action, so that the arc rays passed through the oven tube.

PROBABLE TEMPERATURE OF THE OVEN

Attempts to arrive at the approximate temperature of the oven were made by seeing what could be melted, and also by a thermopile

measurement. With the moderate current of 15 amperes, small pieces of quartz placed in the tube melted and fused together. When the arc current was raised to about 25 amperes, the quartz was not only melted, but rapidly vaporized, forming a thick white deposit inside the tube, in which could be seen tiny globules of sublimed quartz. As we have no idea of the temperature indicated by this, a thermopile measurement was made to find the maximum of radiation in the spectrum. Dr. Pflüger very kindly made this measurement for me with his fluorite apparatus and thermopile. It was, of course, possible to measure only the average radiation from the inside of the tube, but to come nearer to the temperature of the bottom, on which substances to be vaporized lie, the carbon was bored out only as far as the point above the arc, in order to obtain the radiation from the carbon direct, but still the temperature of the carbon doubtless falls off very rapidly as it recedes from the actual point of contact of the arc. The thermopile showed the maximum to lie between 1.6 and 1.5 μ, approaching the latter value as the time went on. Reducing the measurement to the normal spectrum of a black body, and calculating the temperature from Wien's equation, we obtain a value of about 2000° abs., assuming the radiation to be that of a black body. For several reasons it is clear that this must be regarded as a lower limit and not as the real temperature which produces the spectra: (1) The room in which the thermopile was mounted was not fitted with wires heavy enough to carry the high current for a sufficiently long time to give the temperature obtained when photographs were taken. With the maximum current that could be used, the energy-maximum moved steadily toward shorter waves. (2) The calculation considers that the inside of the tube acts as a black body, but this was only in part true, as the end toward the thermopile was not sufficiently closed; so that we obtain a mean value, and the upper part of the tube is necessarily much cooler than the bottom. (3) Quartz vaporizes. For these reasons it would seem safe to assume the temperature of the bottom of the tube as at least 2500° abs.

TRIAL OF A RESISTANCE OVEN

An oven of a different form was constructed and used sufficiently to demonstrate its efficiency. This was essentially a carbon tube heated by the passage of a strong electric current. A graphite tube

of 1 cm inside diameter and 20 cm long was copper-plated at the ends and laid horizontally with the ends on two supports made of thick copper wire, bent and flattened at the end to form a spoon, which made contact with the copper-covered end of the tube; the other end of the wire dipped in a mercury cup in which was also a terminal of a dynamo circuit. To avoid oxidation of the carbon when heated, the tube with its supports was placed in a box of asbestos powder and entirely covered with this, while observation of the interior was provided for by means of an asbestos tube fitting on one end of the carbon tube and passing outside the box, where it was closed by a quartz window.

The tubes at my disposal were of such low resistance that the available current of 50 to 60 amperes served to bring them to a high temperature only when the tube was oxidized enough to be quite thin, after which it lasted but a very short time. The chief observations with this oven were taken visually with metallic calcium in the tube, and the changes in the spectrum of this element will be spoken of later. As a means of obtaining a long column of uniformly heated vapor, with the tube of sufficient diameter to make the continuous spectrum weak, this form of oven is superior to that heated by the arc, and the spectra appear readily when the tube becomes white-hot.

As the materials were not available to use the resistance oven to the best advantage, I have devoted most of my attention in this first work to the oven heated by the arc. The spectra of the several elements studied will now be considered and the results given.

CÆSIUM

The three pairs of the principal series of cæsium were readily produced with the arc oven when cæsium sulphate was used in the tube. This element was investigated in some detail, with the special object of observing the effects of varying temperatures on the members of the principal series. Numerous photographs were made with the oven heated to different degrees by arcs of high and low current.

The photographs taken show clearly that *with rising temperature the series lines of shorter wave-length become relatively stronger*, i. e., for this vapor the maximum of radiation shifts toward ultra-violet. With an arc of 15 amperes a photograph was obtained with the prism

spectrograph in which the pairs λλ 4593, 4555 and λλ 3889, 3877 appeared, the latter very much the weaker. No trace of the third pair λλ 3617, 3612 was to be seen. With a current of 25 amperes the second pair was almost as strong as the first, which did not, however, appear to be overexposed, while the third pair could be faintly seen. Changing the current back to 15 amperes while the oven was still very hot from the trial with 25 amperes, a third photograph was obtained in which the last pair did not appear, but the difference in intensity between the first two pairs was much less than in the first photograph with this same current, the effect being clearly between those of the low and high currents. Other trials were made which confirmed these results, and then an attempt was made to get similar photographs with the small grating. Here a much longer exposure was needed, and the intensity fell off toward the violet much faster than with the prism. However, the effect is here distinctly visible. In the figure, Nos. 1 and 2, are the two photographs with 15 and 25 amperes respectively. The pair λλ 4593, 4555 are of almost exactly the same intensity in both, and are certainly not overexposed, as another plate was taken with longer exposure in which this pair was at least 50 per cent. stronger. The second pair, judged best by its strongest line, is fully twice as strong with 25 as with 15 amperes. The third pair is too weak to reproduce, but can be faintly seen in the negative taken with 25 amperes. The conclusion to be drawn from this result is that *an incandescent vapor follows the law of radiation of a solid body*, as judged by the shift of the maximum in the radiation from the particle which produces this series of lines.

Application to the relative temperature of arc and spark.—From photographs taken in a previous investigation, and others kindly placed at my disposal by Dr. Konen, I have made a comparison of the arc and spark spectra of several elements having lines in series, with reference to the falling off in intensity of series lines toward shorter wave-length. In several of these it is clearly to be seen that in the spark spectrum the members of a series fall off more rapidly in intensity toward shorter wave-length than in the arc spectrum. In the *Na* and *K* spectra this is to be observed in the first and second sub-series. With copper it is very pronounced in the first sub-series

the difference between the first two pairs being much greater in spark than in arc, and it is well known that the third pair, λλ 3688, 3654 does not appear at all in the spark. With calcium the effect is evident in the triplets of the first sub-series, and present, though less pronounced, in the first sub-series of *Mg*. In the spectra of *Cd*, *Zn*, *Hg*, and *Al*, I was unable to detect a difference of this kind, the decrease seeming about equal in arc and spark; and the first sub-series of *Li* seemed to offer an exception to the rule, though the

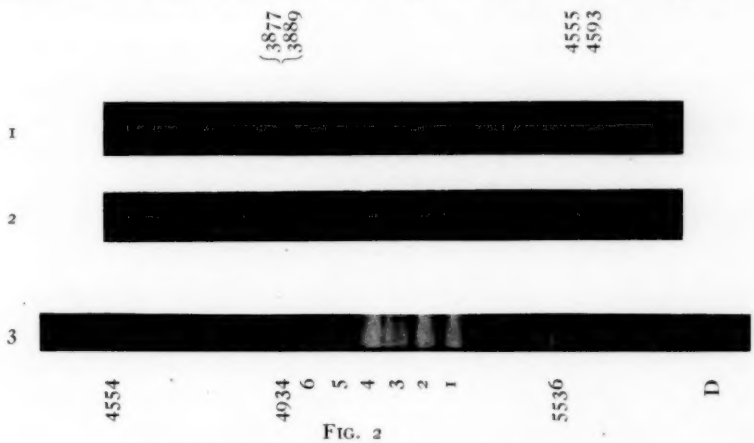


FIG. 2

EXPLANATION OF PHOTOGRAPHS

Nos. 1 and 2 show the two pairs of the cæsium spectrum, as given when the oven was heated by arcs of 25 and 15 amperes respectively. The head of the cyanogen band at λ 3883 appears between the lines of the lower pair.

No. 3 shows the barium spectrum given by the oven with a comparison arc spectrum superposed below. The three barium lines are shown which are discussed in the paper and also the structure of the green band-group.

uncertainty as to whether some of the *Li* lines are double or reversed makes it difficult to decide for this element.

This shift of maximum in the spark toward longer waves, in connection with the behavior of the cæsium series at different temperatures, would point, on its face, to the conclusion that the arc is of higher temperature than the spark, in contradiction to the view generally held; though our knowledge will not enable us to deny that most of the spark properties usually deduced as evidence of higher temperature, such as great brightness with small volume,

richness of spark spectra in ultra-violet lines, etc., may be the result of the more violent electrical action. However, the modern view points to something so different from a thermal radiation in the spark that it seems as if the word "temperature" cannot be used in the same sense for both arc and spark. The more rapid falling off of series lines toward shorter wave-length in the spark scarcely offers in itself enough evidence to offset that on the other side. In the first place, the effect seems not to be so general as we should expect, several exceptions being noted above; and, secondly, it is conceivable that the spark discharges may affect the vibrating particles so as to bring about a shift of the maximum radiation analogous to that given by a true thermal change. But if this is the basis of the behavior of series lines in arc and spark, we have the peculiar condition that the stronger electrical discharge of the spark acts in the same direction as *lower* temperature, shifting the maximum toward the red. Still, such a state is not impossible, as the phenomena of sound tell us that in some cases a more powerful stimulus may strengthen the lower members of a series of vibrations.

CALCIUM

1. *Visual observations of stronger lines.*

a) *With resistance oven.*—With metallic *Ca* in the graphite tube heated by a current, a few observations were made of the changes in the stronger *Ca* lines as the current rose. As the oven became hot, the D lines of sodium appeared, given by impurities in the carbon, then with higher temperature came lines in the red and green which were roughly identified as λλ 6439, 5594, 5589. With still higher temperature these lines broadened and λ 5858 appeared, then the two red lines λλ 6162, 6122. The *g* line, λ 4227, was not observed, though the spectroscope used was not favorable for visual observations in the violet. The group of lines thus obtained proved very sensitive to slight changes of temperature as governed by the current through the tube. A change of 2 or 3 amperes would cause an entirely different intensity relation among the several lines, giving a striking example of the slight change of conditions required to bring about large changes in the appearance of a spectrum.

b) *With arc oven.*—When metallic *Ca* was vaporized in the tube heated by an arc, a higher temperature was doubtless reached, and the development of the stronger lines could be again watched as the tube became hotter; and in this case the continuous spectrum given by the walls of the narrow tube produced frequent reversals. With no chemical in the tube, the trace of *Ca* in the carbon caused the red line λ6439 to appear soon after the D lines. With metallic *Ca* in the tube the relation of emission and absorption for some of the stronger lines could be watched. At first the red *Ca* line and D appeared reversed, given by the glowing tube and the comparatively cool vapor. As the tube became hotter, D became bright, while with the *Ca* line absorption was balanced by emission and the line disappeared. *g* also appeared now. When a small carbon rod was inserted in the tube, giving a stronger background, all of the lines appeared reversed, to become bright again when the rod was withdrawn. When the tube became very hot, with a large quantity of vapor in it, only dark lines appeared, the strong lines in red, yellow, and green, which did not show before, appearing now also reversed. If at this stage the arc was broken, all the lines became bright almost instantly, and remained visible for varying lengths of time, those in the red and green for about 15 seconds.

2. *Photographic observations with arc oven.*

a) *Behavior of the H and K lines as compared to the g line.*—The photographs taken with the oven showed many differences from the arc spectrum, but among these the most interesting was the action of the lines λλ 3968, 3934 known as H and K. These lines, given strongly by all conditions of arc and spark, even when only a trace of *Ca* is present, appeared as bright lines in the spectrum given by my oven only under maximum conditions of temperature and vapor density, and then very faintly. With a large amount of metallic *Ca* in the tube, a long exposure and an arc current of 25 amperes, the H and K lines could be detected as very faint narrow lines, with the aid of a comparison arc spectrum. Under these conditions, *g* is overexposed and broadly reversed, the series triplets with lines of greater wave-length at 4455 and 3644 are very distinct, the first-named triplet being strong, as is also the group of six lines from λ4319 to λ4283. The non-series triplet beginning at 4586 is absent,

as is also the pair 3737, 3706, which has the same vibration difference as H and K, and is strong in the condensed spark. The higher temperature of the arc is probably in part responsible for this difference, but the magnitude of the change, as well as the action of H and K in spark spectra[1], where they are favored by the highly condensed spark and reduced relatively to *g* by self-induction in circuit, point to the electrical conditions in the arc and spark as being necessary to give these lines their usual intensity.

b) ***Unsymmetrical reversal of the g line.***—The *g* line shows an apparent displacement in some grating photographs. In these the comparison arc spectrum usually gives *g* reversed, and in several cases where the oven spectrum gave *g* sharp it was seen to coincide with the edge rather than the middle of the reversed arc line. A measurement on one plate from the sharp line given by the oven to the middle of the reversed arc line gave a difference of 0.48 tenth-meter toward greater wave-length, the direction of apparent displacement being the same as for H and K. On this same plate numerous sharp lines were perfectly continuous in the two spectra. However, when the reversal of *g* was narrower, its apparent displacement was less, and on some plates when *g* was not reversed in the arc it appeared continuous with the sharp line of the oven. Thus the evidence favors considering the action of *g* as an unsymmetrical reversal.

c) ***Reversal effects of Ca vapor.***—An experiment was tried with *Ca* which may be put to general use in the study of reversal phenomena, if the apparatus is so altered as to give a longer column of vapor. A large amount of *Ca* vapor was produced in the tube from the metal, and a carbon arc containing *Ca* was placed at the end of the oven so that its light should pass through the intensely heated vapor to the grating. The absorption possibility of *g* as compared with that of the other *Ca* lines was the most striking result of this trial. The low dispersion made it difficult to decide whether the lines other than *g* were reversed or not, but at any rate only *g* had its reversal increased by passage of the arc radiation through the vapor in the oven. The reversal of *g* was always wider than with the simple arc, and became broader as the vapor in the oven was

[1] A. S. King, *Astrophysical Journal* **19**, 225–238, 1904.

more intensely heated, reaching a width of several tenth-meters at maximum temperature of the oven. Probably the increased quantity of vapor and higher temperature worked together to give this result.

3. *Band spectrum of calcium.*—The well-known *Ca* bands in the orange and red, which appear sometimes in the arc, were very brilliant and constant with the oven. In addition to these, the oven gives a set of much weaker bands in the violet which I believe have not been previously observed. Five bands are visible in this group, and, while rather diffuse, appear to be shaded toward the red. These were obtained in grating photographs, and I have measured the positions of the strongest part of each band, as well as the definition would allow, as follows:

3691	faint, diffuse
3766	diffuse
3835	well-defined edge, shaded toward red
3892	well-defined edge, shaded toward red
3959	diffuse

These bands appear with the oven at moderate temperatures and with either metallic *Ca* or the chloride in the tube, strongest with the latter. This points to the oxide as a possible cause, air being present, though no careful tests have been made on this point as yet.

STRONTIUM

1. *Line spectrum.*—With strontium chloride in the oven, the spectrum is much less sensitive than that of calcium. However, some of the stronger lines were obtained and showed a relative intensity among themselves quite different from that in the arc. The lines λλ 4607, 4215, 4077 are considered homologous, from their position and general behavior, to the *Ca* lines *g*, H and K respectively; and the changes made by the oven are similar to those observed with the three *Ca* lines, though not so pronounced. λλ 4215 and 4077 are connected by the vibration difference 801.5, which occurs several times in the *Sr* spectrum. In the arc they are always strong, almost, if not quite, as strong as λ 4607. The oven, however, gives only the faintest traces of this pair, while λ 4607 is of considerable intensity, much the strongest line in the spectrum.

2. *Band spectrum.*—As with *Ca*, the oven serves to bring out a strong band spectrum. The bands in the orange were observed visually and were very strong. In addition, my photographs show a much weaker set of bands in the violet, which I believe are new. Four bands appear here, whose approximate wave-lengths and appearance are as follows:

3937	sharp edge, shaded toward red
3962	sharp edge, shaded toward red
3992	diffuse
4014	diffuse

The first two bands have very distinct edges toward the ultra-violet. No resolution into lines is given by the dispersion used, these bands evidently being of much denser structure than those in the orange.

BARIUM

1. *Line spectrum.*—Barium chloride was used in the oven, and here again the interest centers around three lines, λ 5536 and the pair λλ 4934, 4554, which were the only ones obtained in this region. The last two, a strong arc pair, are very faint, only a trace of λ 4934 being visible, while λ 5536 is strong. The ratio of intensities in oven and arc for λ 4554 is about 1:20, for λ 5536 about 3:4 (see Fig. 2, No. 3).

The lines λλ 4934, 4554 are shown by their behavior in the magnetic field[1] to be of the same type as λλ 4215, 4077 of *Sr*, and H and K of *Ca*. This homology is borne out by the action of the three pairs in the oven spectrum. These pairs, moreover, being of the same magnetic type as the D lines of *Na*, are considered as probably members of the principal series for their respective elements, the other members being as yet unknown. If this is the case, however, we have here an exception to the rule that principal series lines are given by the simplest conditions, since the weakness of the pairs in the oven spectrum shows that an abnormal stimulus is required to give them the intensity which they have in arc and spark.

2. *Band spectrum.*—The set of bands in the green-yellow are given very strong by the oven. Their structure is worthy of more detailed study than I could make with the dispersion available, and, judging from visual observations of the bands of *Ca* and *Sr* in the

[1] H. Kayser, *Handbuch der Spectroscopie*, II, p. 671.

less refrangible part, these are very similar. Fig. 2, No. 3, shows these *Ba* bands, somewhat overexposed to bring out the weaker portions. While the bands evidently have their heads toward the violet, the successive members of the group show a shift of the maximum intensity in each band. The first band at the red end of the group has its intensity concentrated in the head, this being so strong as to be ill-defined. The second band has a sharply defined head with a considerable extension toward the red. In the third band the whole structure is resolved into fine lines of nearly equal intensity, the head being stronger and reversed. In the fourth band, the red end, which we may call the "tail," is much stronger than the head, which is still visible. The fifth shows the intensity more concentrated in the tail, with only a trace of the middle, while in the sixth only the tail is visible.

A second and new group of bands appears in the ultra-violet, very weak in comparison with the green series. I have measured eight bands here, some very faint, but two of them having fairly sharp edges toward the red. The bands are too weak to decide if a structure similar to that of the green bands is present here. The approximate wave-lengths follow:

3646	diffuse	3822	diffuse, fairly strong
3694	diffuse	3872	well-defined edge toward red
3725	diffuse	3922	well-defined edge toward red
3768	diffuse	3961	faint

COPPER

Metallic copper in the oven gave a combined line and band spectrum.

1. *Line spectrum.*—A comparison of the lines obtained in my oven with the behavior of the same lines in the arc and spark spectra previously studied[1] leads to some interesting conclusions. The lines given by the oven are few and are not the lines most prominent in the arc. I have obtained only λλ 5106, 5700, 5782, there being no trace whatever of the pair λλ 3274, 3247, which are always the strongest lines in the arc or spark spectrum, of the first sub-series pairs λλ 4023, 4063, 5153, 5218, always strong in the arc, and numerous other prominent lines. The action of λλ 3274, 3247 is significant as indicating that the chemical action in the oven is very weak. W. Lansrath,[2]

[1] A. S. King, *Astrophysical Journal*, **20**, 21–40, 1904. [2] *Dissertation*, Bonn, 1904.

who recently photographed the oxygen-coal-gas flame spectrum of *Cu* with the same grating and same sort of plates, records these lines as always appearing strongly in the flame, usually reversed. In my photograph, the comparison arc spectrum gives the lines in their usual strength, but the oven spectrum shows nothing beyond the cyanogen band λ 3590, though the temperature of the oven must be considerably higher than that of the flame. The conclusion to be drawn, then, is that the conditions other than high temperature which produce these lines in the flame are absent or very weak in the oven. The temperature of the oven is not high enough to give lines of so short wave-length in any spectrum studied, so we should not expect them to appear if the radiation of the oven is chiefly a temperature effect.

The strength of the green lines 5106, 5700, 5782, combined with the absence of the pair 5153, 5218, is approached in the arc only when the current is very weak, as 0.5 ampere, and still closer when with a current of 1 ampere the outside layer of luminous vapor was projected on the slit. In this latter case the weakness of the pair compared to λ 5106 was striking. As the current rose above 0.5 ampere, the pair increases in relative strength until at about 6 amperes its weaker member λ 5153 is equal to λ 5106, and with still higher currents surpasses it in strength. As was noted in the former paper, the arc with high voltage and only 0.3 ampere, given by a succession of flashes, resembles in many respects the arc with high current, unusual conditions apparently being given by the interruption. In the spark, λλ 5153, 5218 are always strong except under those conditions, such as the spark with self-induction or with hot electrodes, in which the relative intensities of lines approach in some degree those of the arc.

Thus the copper lines as given by the oven would seem to indicate conditions a grade lower than the weakest arc; while the total absence of the strong ultra-violet pair speaks for an absence or great weakness of luminous processes other than temperature.

2. *Band spectrum.*—The oven proved very efficient in producing the banded spectrum when metallic *Cu* was vaporized in the tube. The bands with heads at λ 4005 and λ 4280, both running toward the red, are given very distinctly, with a fine resolution of their compo-

nent lines. In the prismatic spectrum I obtained the band λ 4280 strongly reversed. These bands in the flame were photographed by Hartley and recently measured by Lansrath. Besides these, the bands at λ 4649 and λ 4689 appear, which have been observed in the flame; and in addition the oven gives three other bands evidently belonging to the group and of the same dense structure. These are stronger than the two bands already known, but are probably concealed by the continuous ground in the flame spectrum. I have measured the heads of these as λλ 4598, 4547, 4499. Like the other bands, their edges are toward the violet and are fairly sharp.

IRON

The impurities in the carbon tube gave a large number of iron lines, and the number was not greatly increased when iron was vaporized in the tube. This metal showed very well the differences between arc and oven spectra, many relative differences in intensities of lines appearing. In the best photograph obtained, with the spectrum of the iron arc beside that from the oven, several lines in the blue were of the same intensity in both. These were λλ 4482, 4461, 4427, 4376. Many arc lines as strong as these, and some stronger, did not appear at all with the oven, and others were relatively much weakened. In the following table some of the stronger lines are selected and their intensities compared, to give an idea of the sort of differences which appear in the two spectra:

λ	Arc	Oven	λ	Arc	Oven
3878.75	8	2	4308.09	10	2
86.45	6	2	25.97	10	2
95.83	4	1	76.11	2	2
99.89	4	1	83.71	15	3
3920.42	5	1	4404.95	12	2
23.10	5	1	15.31	10	½
28.10	6	1	27.50	3	3
30.49	6	1	61.83	2	2
69.41	8	0	82.39	2	2
4005.42	8	0	4528.80	6	0
45.99	12	1	5269.72	8	2
63.77	11	1	5328.21	6	3
71.92	10	1	71.67	6	3
4132.25	8	½	97.32	3	1
44.05	10	½	5429.81	3	1
4250.99	9	0	.....	.	.
60.68	9	0	.....	.	.
71.95	12	2	.....	.	.

This table shows something of the differences which result from the conditions of the arc, as compared with the lower temperature of the oven combined with absence of electrical action.

MAGNESIUM

With either metallic *Mg* or the carbonate in the tube, a rather weak line spectrum appeared consisting of the triplets with strongest lines at λ 3838 and λ 5184 and the arc line λ 4571.31. The relative intensity of these lines is very different from that of the arc, and the strong arc lines λλ 4352, 4703 do not appear with the oven at all. The intensities of the lines in the two cases are approximately as follows:

λ	Arc	Oven
3829	15	12
3832	20	15
3838	40	30
4352	5	0
4571	2	50
4703	8	0
5167	8	8
5173	12	12
5184	20	20

From this it is seen that the violet triplet is weakened by the oven with respect to the green triplet, while λ 4571, one of the weakest arc lines, attains a quite abnormal intensity. My results for *Mg* permit of little comparison with those of Nasini and Anderlini[1] beyond the fact that my photographs do not show the lines which they consider to be those of nitrogen, given when the oxygen is used up by combination with *Mg*.

NEGATIVE RESULTS WITH MERCURY AND ZINC

These metals were used in large quantities in the oven at maximum temperature without any of their lines being obtained. It may be that their spectra require still higher temperature or electrical action, but it is quite possible that when such metals are vaporized in air they oxidize before the vapor is heated sufficiently to emit.

FURTHER OBSERVATIONS

Lead.—The strong arc line λ 4058 proved very sensitive, appearing almost always from impurities in the carbon. When metallic lead was vaporized in the tube this line appeared strongly and also the

[1] *Loc. cit.*

two lines λλ 3640, 3684, these last, as compared with λ 4058, being much weaker than in the arc.

Aluminium.—Impurities in the carbon always gave the pair λλ 3944, 3962, and when the metal was introduced these lines were very strong.

Sodium.—The D lines appeared under all conditions, being extremely sensitive and appearing long before the oven reached a temperature sufficient to produce other lines. Metallic *Na* could not be used in the oven to give a greater vapor density, as it appeared to act on the cementing material of the carbon, causing immediate disintegration.

Manganese.—The lines of the violet triplet λλ 4031, 4033, 4035 are noteworthy for their sensitiveness and easy reversibility. The triplet always appears strongly, given by impurities, and this small quantity of the vapor sufficed to give the lines reversed when a continuous ground was produced. In these properties this triplet ranks with the D lines and *g* of calcium.

Lines given by small impurities.—As an example of the usefulness of the oven in bringing out lines when only a minute quantity of the element is present, it may be of interest to note the elements represented in a photograph taken with cæsium sulphate in the tube, the sensitiveness of the plate extending only to about λ 4600. Here the lines other than *Cs* could come only from impurities in the salt or in the carbon.

Sr	4607.51
Cr	4289.92, 4275.01, 4254.52
Ca	4226.90
Rb	4215.75, 4202.00
Ga	4172.22
Pb	4058.00
K	4047.42, 4044.30
Mn	4034.62, 4033.21, 4030.92
Al	3961.71, 3944.20
Fe	28 lines identified

These, with the D lines of *Na*, the *Cs* lines and the cyanogen band 3883 give a total of thirteen elements represented in the spectrum given by a "chemically pure" salt in the tube.

Arc spectrum given by ionized vapor.—It was shown in the course of these experiments that vapor coming directly from the arc, espe-

cially when confined, gave the arc spectrum, though quite out of the path of the current. Several times when a hole was burned in the bottom of the carbon tube, the arc spectrum appeared at once from the vapor streaming up into the tube, though the arc itself was entirely below. Also when the tube was moved so that the arc struck close to its end instead of at the middle, the vapor rising past the end showed the arc spectrum of the carbon and impurities. The regular position of the arc striking the middle of the tube did not allow of any arc vapor coming into the region projected on the slit.

Effect of water vapor.—To see if the hydrogen lines would appear from water vapor in the oven, as they are known to come when water is dropped into the arc, a current of steam was passed into one end of the tube, the other being closed by a window at the end of the asbestos extension tube; while a small hole in the side of the carbon near its middle, inside the inclosing blocks, gave an outlet for the steam, leaving the tube almost air-tight. The hydrogen lines did not appear but other lines, evidently belonging to impurities in the carbon, were rendered very bright by the contact of the steam. These were in the green and red, about λ 5500 and λ 6200 respectively, and may have been calcium lines which have only a moderate strength in the arc; but as the observations were made visually with a small dispersion, they were not certainly identified. The steam caused the red line to become very brilliant and reverse, and a little farther in the red a very diffuse banded structure appeared with much steam in the tube, not distinct enough for identification. This strengthening of certain lines through the presence of water vapor may have interesting applications in the further study, though at present its process is obscure.

DISCUSSION OF RESULTS

The chief significance of the foregoing results is that they have been obtained by a method which, while giving a high temperature, excludes the electrical action always present in the arc or spark. The electrical action here meant is that which arises from the vapors carrying the electric current. The arc is used merely as a source of heat. The intense heat must produce a certain degree of ionization of the vapor inside the tube, and electrical action in this sense is present; but this would be true if the tube could be heated to the same degree by a gas flame or coal furnace.

Chemical action is undoubtedly present when the oven is used in air, and the complete exclusion of possible chemical action would seem to be impossible, since the vapor must always be heated in a closed space, and this even if evacuated would offer the possibility of chemical action between the vapors and the walls of the containing vessel, as combinations might be formed under such conditions which are unknown at ordinary temperatures.

Allowing then for the possibility of such action by other agents, my evidence in favor of temperature as the chief agent in giving the observed effects lies mainly along three lines:

First, in every case which was tried, the production of a strong continuous ground by the introduction of a small carbon rod in the oven tube was found either to quench or reverse all emission lines, showing that the radiation of a black body at the same temperature was always stronger than that of the luminous vapor—a condition which might or might not be true if these lines owed their radiation to sources other than temperature. Even the D lines followed this rule, though they appear at such comparatively low temperatures as to suggest a chemical luminescence. If the tube contained glowing solid matter, lines were seen reversed against the background thus given and bright in the free part of the tube.

Second, the spectrum given by the oven appears to have a limit at its violet end which is never overstepped, even when lines usually strong in the arc or spark should appear slightly beyond this limit. The temperature which I have been able to produce gave no lines in my photographs below λ 3500, though the plates were sensitive to the arc spectrum as low as λ 2200. The copper spectrum gave the best example of this action. As has been noted, no trace appears of $\lambda\lambda$ 3274, 3247 which in all arc and spark spectra in air are much the strongest lines of the spectrum, while lines are given by the oven which in the arc are much weaker than this pair. If conditions other than high temperature are necessary to produce these lines, such conditions are not strong enough in the oven to bring out lines beyond the limit apparently set by the temperature.

The third evidence may be drawn from the shift of the maximum in the cæsium series with higher temperature. Unless the chemical action in the tube is capable of changing the maximum of radiation

as the action becomes more vigorous (which, so far as I know, has not been observed in other experiments), the only alternative seems to be to recognize the temperature as the agency in shifting the maximum, and, if so, as the cause of radiation.

The foregoing observations have been obtained with the apparatus in its simplest form, the purpose being largely to develop the possibilities of the method. Numerous refinements are possible, not only in improving the efficiency of the oven, but in excluding possible chemical action. The work next in view along this line is the construction of the oven in a closed chamber which may be either evacuated or filled with pure gases.

SUMMARY

The chief results may be summarized as follows:

1. The oven produces emission spectra containing numerous lines whose relative intensities are very different from the lines of the arc spectrum.

2. The method is especially favorable for the production of banded spectra.

3. The changes in intensity of the cæsium series lines with the temperature indicate that an incandescent vapor follows the law of radiation of a solid body.

4. A comparison of series lines in arc and spark spectra of several elements points to an effect by altered electrical action similar to that of changed temperature.

5. The calcium spectrum from the oven shows: (*a*) great sensitiveness to slight changes of temperature; (*b*) a peculiar behavior of the H and K lines, which appear only at maximum temperature and then very weak; (*c*) *g* shows an unsymmetrical broadening of reversal, giving an apparent displacement; (*d*) using the vapor in the oven as absorbing medium showed the absorption of *g* to be much greater than that of other calcium lines and to vary with the temperature of the oven.

6. The pairs of homologous lines in the spectra of *Ca*, *Sr*, and *Ba*, belonging to the same magnetic type, are in each case much weakened in the oven spectrum as compared to the arc.

7. The oven spectrum shows new groups of bands in the spectra

of *Ca*, *Sr*, *Ba*, and *Cu*. The structure of the green band-group of *Ba* seems to result from a shift of maximum intensity through the successive bands of the group.

8. The relative intensities of copper lines given by the oven approach those of the very weak arc. The absence of the ultra-violet pair speaks for temperature as the chief agent in producing the spectrum.

9. In many cases a very small amount of a substance in the oven served to give characteristic lines.

10. It was shown incidentally that ionized vapor direct from the arc, when confined, would give the arc spectrum, though out of the path of the current.

11. Water vapor in the oven had the effect of intensifying certain metallic lines.

I wish to express to Professor Kayser my appreciation of the interest he has taken in the work and of the valuable advice he was always most ready to give.

PHYSICAL INSTITUTE, UNIVERSITY OF BONN,
October 1904.

THE TEMPERATURE OF THE SOLAR ATMOSPHERE

By ARTHUR SCHUSTER

Two years ago I published in this *Journal* an investigation on the "Absorption and Radiation of the Solar Atmosphere," which has recently been commented upon by Mr. Very. Scientific discussion is unprofitable if criticism is based on misunderstandings for which the criticised author is not responsible; and that this is the case in the present instance appears from the two following sentences, among others, quoted verbatim from Mr. Very's paper: "The symbol I is used for photospheric radiation, and F for the 'radiation of a perfectly black body which is at the temperature of the shell' constituting the absorbing atmospheric layer. This supposition implies that the absorbent matter consists of perfectly black particles suspended in the medium."

Everybody knows that the function of temperature and wave-length which expresses the radiation of a black body is a fundamental function which must enter into every discussion of radiation and absorption. Yet, for the reason that I have introduced the symbol F for this function, and for that reason alone, Mr. Very accuses me of having tacitly introduced an assumption into my equations which begs the question. There is, of course, no foundation for Mr. Very's conclusion. A glance at the equation which forms my starting-point would have shown him that I took the radiation of the layer in question to be proportional to kF, and as k may have any possible value between zero and infinity, and may also depend on the wave-length, every possible case of absorption is included in my equations.

Among the questions raised by Mr. Very the only one on which argument is possible is the location of the absorbing layer. I ought perhaps to have been a little more explicit on this point, but, as regards the main purpose of the investigation, it was a point of secondary importance only. It will be remembered that my object was to explain the apparent diminution of intensity of radiation observed near the Sun's limb. The obvious explanation that an

absorbing shell was the cause of the diminution apparently did not fit the facts, as it gave a law for the rate at which the radiation diminished which was not consistent with observation. I showed that observation and theory were easily reconciled by taking account of the *radiation* as well as of the absorption of the interposed shell. The amount of radiation necessary showed that the absorbing layer must have a temperature not very much less than that of the photosphere. I added that I saw no reason to look for a different region in the Sun's surroundings for the cause of the observed diminution of radiation than that which gives the Fraunhofer lines. I obviously did not here refer to the region of the chromosphere. Nor did I mean my words to apply to the region which appears at the beginning and end of eclipses and gives us what is called the flash spectrum, though there may here have been a reasonable ground for misunderstanding. All I meant to imply was that, because in the region in question absorption outweighed radiation as regards the continuous spectrum, it would also do so for the line spectra of metals, and that therefore this region must contribute to the Fraunhofer absorption lines.

As misunderstandings seem so easily to arise, it is perhaps worth pointing out that, although for the purpose of facilitating mathematical analysis it is sometimes necessary to treat the upper portion of the same body as made up of distinct layers, having different temperatures and possibly different absorbent properties, the result of the analysis would, at any rate, in the present problem be the same had I taken the variation of temperature to be gradual instead of sudden. Even for the purposes of ordinary discussion we speak of the photosphere and of the absorbing layer, without wishing to imply that there is an abrupt transition from one layer to the other. If anyone desires to include the region in which radiation just falls short of absorption under the name of the photospheric layer, I have no objections. As far as this portion of the argument is concerned, it is one of nomenclature only.

I should probably not have taken space for an answer to the objections which have been raised, with insufficient cause, though they have been indorsed by an abstractor in the *Beiblätter*, had I not wished to correct an error for which I cannot offer any excuse.

The layer which for shortness I call the absorbing layer has a temperature which can be calculated in two different ways, if the temperature of the photosphere is assumed to be known. We may use for the purpose either the wave-lengths at the maxima of radiation, or the relative values of the radiation at the maxima. The ratio of the wave-lengths at these maxima, which also, taken inversely, is the ratio of the temperatures, was correctly given in my paper as 0.84. But the temperature was erroneously stated to be as the fourth power of the maximum radiation, while it ought, of course, to have been put equal to the fifth power. This improves the agreement. The maximum of the photospheric radiation in terms of an arbitrary unit is somewhere between 1.7 and 1.75, and the maximum radiation of a black body at the temperature of the absorbing layer in terms of the same unit is shown by my curves to lie about 0.62. This gives for the calculated ratio of temperatures a value somewhere between 0.81 and 0.82, numbers indicating a remarkable coincidence with the ratio of 0.84 calculated by the first method. In the rough examples given in my paper I took 10,000° for the temperature of the photosphere. To be more exact, we ought to put about 6,000° for the combined radiation of the two layers. This would give about 6,700° for the photospheric layers and about 5,450° for the temperature of the absorbing layer. With the exception of the numerical error now corrected, the reconsideration of the whole problem leads me to reaffirm all previous conclusions, which may be more strictly formulated thus:

There is a stratum near the Sun's surface having an average temperature of approximately 5,500° C., to which about 0.3 of the Sun's radiation is due. The remaining portion of the radiation has an intensity equal to that due to a black body having a temperature of about 6,700° C.

This conclusion is based on the supposition that the effective temperature of the Sun is 6,000°, and that the law of diminution of the average intensity of radiation with increasing distances from the Sun's center is correctly represented by Mr. Wilson's numbers, as quoted in my previous communication.

THE UNIVERSITY,
Manchester, England,
December 1904.

THE WORK OF THE RUMFORD SPECTROHELIOGRAPH

By GEORGE E. HALE

A paper on the Rumford spectroheliograph, published by Mr. Ellerman and myself as Part I, Vol. III, of the "Publications of the Yerkes Observatory," has been reviewed by several writers, to whom we are indebted for the careful discussion they have given to the work of the instrument.[1] In the course of these reviews certain questions have been raised regarding our interpretation of phenomena shown in the photographs. It is my object in the present paper to reply to these questions, in order that the true purpose and function of the spectroheliograph may be made as clear as possible.

Taking the reviews in order of publication, we come first to the interesting and valuable article by Mr. Evershed in the April 1904 number of *The Observatory*. Since Mr. Evershed's own work with the spectroheliograph dates back to 1892, it is obvious that his criticisms deserve most careful consideration. In one particular Mr. Evershed's interpretation of the spectroheliograph results differ from the one which we have employed as a working hypothesis. He is inclined to adopt the view that photographs taken with the second slit set on H_1 or K_1 represent the true faculæ, rather than the low-lying, dense vapor of calcium. His remarks on this subject are as follows:

> In discussing the results obtained in this way, Professor Hale adopts this view as a "working hypothesis," namely, that the calcium flocculi are depicted sectionally in at least three different levels above the photosphere, and the evidence afforded by these photographs certainly seems to bear out this idea. A serious objection, however, would seem to follow from the fact that in the photographs

[1] J. Evershed, "The Rumford Spectroheliograph of the Yerkes Observatory," *The Observatory*, April 1904. W. J. S. Lockyer, "A New Epoch in Solar Physics," *Nature*, April 28, 1904. E. Walter Maunder, "The Solar Atmosphere at Different Levels," *Knowledge*, July 1904. H. Deslandres, "Sur la photographie des diverses couches superposées qui composent l'atmosphère solaire," *Comptes Rendus*, June 6, 1904. B. Hasselberg, "En ny spectroheliografisk metod," annual address before the Academy of Sciences, Stockholm, March 28, 1904. W. H. Julius, "Spectrohelio-graphic Results Explained by Anomalous Dispersion," Royal Academy of Sciences, Amsterdam; Proceedings of the Meeting of June 25, 1904.

of the spectrum itself the true reversals of H and K seem to be entirely confined to the central H_2 and K_2 region of the lines. Only in the rare cases of violent eruptions are there ever any signs of lateral spreading of the bright lines; and the shading on each side appears almost always to be uniformly dark, except only where it is crossed by the faintly bright continuous bands of the true faculæ. These bands, however, sometimes give a deceptive appearance of true reversal of the shading, as is well seen in Plate II, Fig. 2.

An alternative hypothesis would be that the K_1 images really represent the true faculæ, and are photographed by the continuous spectrum superposed upon the K band. On this view they cannot be regarded as low-level *calcium* vapor. It is possible, however, that the true calcium emission may become evident where shown up upon the dark background of a spot. The interesting comparisons given on Plates V and VI would have been more instructive on this point had the region photographed been situated near to the limb, where the faculæ proper would have shown up in much greater contrast.

The increase in brightness of the flocculi with the slit set nearer the center of the band, but still outside K_2, might be explained as an effect of contrast only. It is to be borne in mind, however, that in this position, so near to K_2, there is the possibility of partial reflection of the bright K_2 from one of the (highly polished) jaws of the slit itself.

In favor of Mr. Evershed's view, we have the following arguments:

1. If, as Mr. Evershed believes, the dense calcium vapor which gives rise to the H_1 and K_1 bands lies "appreciably below and between the highest summits of the faculæ," we would naturally expect the spectroheliograph to show the true faculæ when the second slit is set on these bands; for the increased absorption due to the bands would cut down the brightness of the background, and leave the faculæ, assumed to be unaffected by this absorption, standing out in strong contrast. Moreover, on this assumption the contrast should increase as the second slit is moved nearer to the center of the bands, since the corresponding increase in the intensity of the dark bands would tend to reduce the brightness of the background upon which the faculæ appear in the photographs.

2. Mr. Evershed argues that if the H_1 and K_1 photographs really represent the low-lying calcium vapor, these dark bands in the solar spectrum should give indications of reversal where they cross the flocculi. As a matter of fact, such reversals do not seem to be present, at least in a great majority of cases.

Without regarding it as free from objection, I am still inclined to retain the working hypothesis employed in our former paper. The following considerations have led to this conclusion:

1. If Mr. Evershed is right in his view that the faculæ overlie the dense calcium vapor represented by H_1 and K_1, the continuous spectrum of the faculæ should cross these dark bands with no diminution of brightness. A clear understanding of the spectrum in this region can be obtained only from a study of photographs taken with very high dispersion. Plate XIV is a reproduction of such a photograph recently secured on Mount Wilson with a Littrow spectrograph of 18 feet focal length. The 4-inch plane grating, having 14,438 lines to the inch, which was formerly used with the Kenwood spectroheliograph, was employed in the present instance with an objective of 4 inches aperture and 18 feet focal length, serving for both collimator and camera. An image of the Sun was formed on the slit of the spectroscope by an objective of 6 inches aperture and 61½ ft. (18.74 m) focal length, supplied with light by a 15-inch cœlostat.[1] The photograph reproduced in Plate XIV was taken in the third-order spectrum. The scale is sufficient to show that the continuous spectrum of the faculæ rapidly decreases in intensity as it approaches the center of H_1 and K_1, where it almost entirely disappears. All of the photographs I have examined show this effect with greater or less clearness.

It seems to me that under these circumstances we should hardly expect the photographs to show the *faculæ* with increasing contrast, as the slit is moved from the edge toward the center of H_1 or K_1. On the contrary, we should expect the contrast of the faculæ to decrease rapidly, whereas the phenomena we have attributed to low-level calcium vapor steadily increase in *contrast*, though their absolute intensity diminishes.

In the light of existing evidence, I regard the photosphere as composed of innumerable clouds of condensed vapor, forming the summits of columns extending radially outward from the Sun's interior. The distance from the Sun's center at which condensation occurs depends upon the temperature gradient and upon the nature of the vapors which compose the columns. Probably only a few easily condensable substances are represented in the photospheric clouds. At any rate, hydrogen, helium, and calcium rise above the point of condensation, and continue upward into the chromosphere and

[1] The entire apparatus was extemporized for use pending the erection of the Snow telescope on Mount Wilson.

prominences. Magnesium, sodium, iron, and other substances represented in the flash spectrum also rise above the photospheric level.

At certain parts of the disk, where the convection currents rising from the Sun's interior are especially strong, the level of condensation is carried farther from the center because of the higher temperature. These regions are the faculæ, which therefore resemble the other parts of the photosphere in structure, though the photospheric clouds which compose them attain higher elevations.

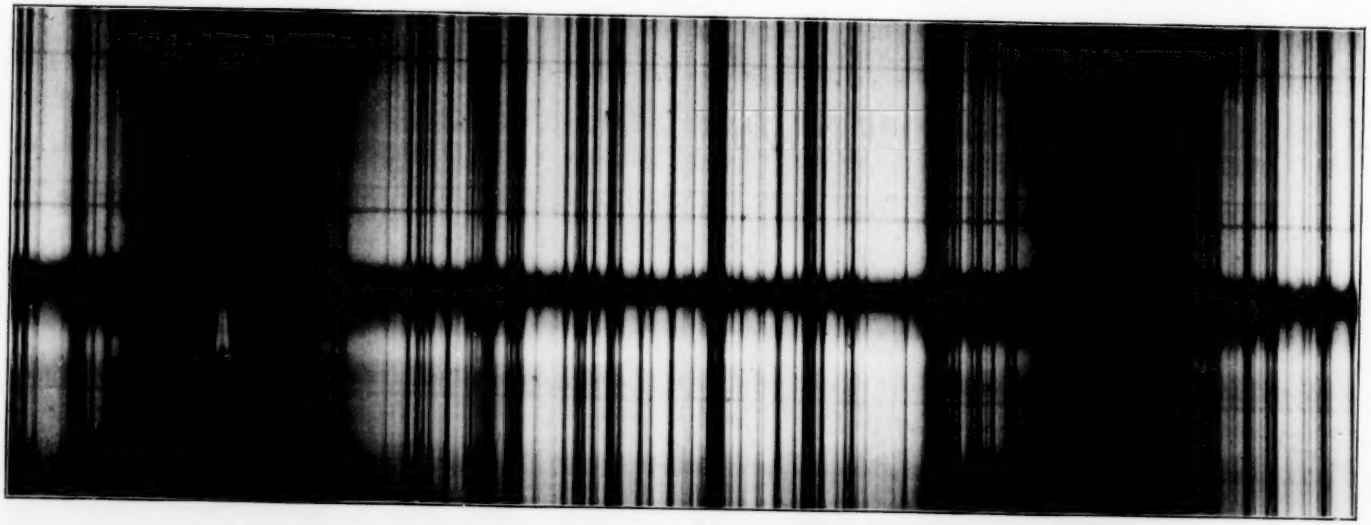
The height at which condensation occurs in the faculæ is ordinarily below the level attained by calcium vapor of such density as to produce bands of fully one-half the width of H_1 and K_1 in the solar spectrum. This is indicated by the fact that the continuous spectrum of the faculæ is usually weakened by absorption over more than half the width of these bands (Plate XIV). In general, the denser calcium vapor probably rises from the interior in the same columns with the vapors which condense to form the faculæ, though this does not always appear to be true. Hence, photographs of the faculæ, taken directly, or with a spectroheliograph having its second slit set on the continuous spectrum, will usually give forms resembling those obtained when the second slit is set near the edge of H_1 or K_1. The calcium vapor expands as it rises, and consequently the forms of sections of the flocculi, corresponding to higher levels, defined by the position of the second slit as it is set nearer the center of the band, will continue to show wider divergencies from the forms of the faculæ.

I believe that the evidence afforded by the flash spectrum as to the elevation attained by the denser calcium vapor will not be found to conflict with these views.

2. I frankly admit that I can offer no satisfactory reply to Mr. Evershed's second objection It certainly seems that H_1 and K_1 should show evidences of reversal over the flocculi, if they represent the calcium vapor in them. But one fact must not be overlooked: since calcium vapor undeniably extends deep into and below the photosphere, and since it has been shown to be so conspicuous in the H_2 and K_2 flocculi, it must play a very important part and

[1] This is clearly shown on the untouched photograph from which Plate XIV is made, though it may not come out well in the reproduction.

PLATE XIV



DECREASED INTENSITY OF CONTINUOUS SPECTRUM OF THE FACULÆ ON THE H_1 AND K_1 BANDS

exhibit a wide range of density in the intermediate region. Hence, we should expect photographs taken with the second slit set on H_1 or K_1, close beside H_2 or K_2, to show bright areas intermediate in form between the faculæ and the H_2 or K_2 flocculi. This is precisely what we do get. These bright regions are greater in area than the faculæ, though they are inferior in this respect to the H_2 or K_2 flocculi. The area, as well as the contrast, of the flocculi increases as the second slit is moved toward the center of the band. Careful tests have been made to determine whether this increase in area (which is accompanied by changes in form) is to be attributed to an actual increase in the area of the flocculi. The results show, in my opinion, that the difference cannot be attributed to any effect resulting from increase of contrast arising from change of exposure time, or to other similar causes. Nor do I think the changes in form can be accounted for wholly by the effect of calcium vapor over the dark regions of sun-spots, where Mr. Evershed considers it might make its appearance felt. Reflection from the slit jaws, in such a way as to produce the phenomena observed, seems to me entirely out of the question.

If the objects photographed with H_1 or K_1 light were the faculæ, their forms should remain the same, whether the second slit be set on the continuous spectrum or at any point on the H_1 or K_1 bands (excepting, of course, at the center of the bands, where H_2 or K_2 light would enter). As we have already seen, however, neither the forms nor the areas remain constant.

Professor Schuster's very important paper on "Radiation through a Foggy Atmosphere" [1] has removed the difficulty of accounting for the bright H_2 and K_2 lines on the dark bands H_1 and K_1. In fact the bright reversals are precisely what we might expect, in view of the exceptional emissive power of these lines, and the great height to which calcium rises above the photosphere.

Dr. W. J. S. Lockyer, who reviews our paper in *Nature*, takes no exception to our working hypothesis on the photography of sections of flocculi corresponding to different levels. On the contrary, he gives a very lucid account of the method, illustrated by a diagram which brings out the principle involved in a very satisfactory manner.

[1] *Astrophysical Journal*, **21**, 1, January 1905.

Professor Hasselberg's address and Mr. Maunder's recent article in *Knowledge* also give a clear account of photography at different levels; but as they contain no criticism of our results, these papers require no reply.

Dr. Lockyer's difficulty relates to the question of bright and dark flocculi, especially with reference to the distribution of hydrogen and calcium vapor in the solar atmosphere. After referring to hydrogen and calcium in the flocculi, Dr. Lockyer remarks: "Since the *existence* of each of these substances on the Sun's disk is indicated by *bright* markings, it is not quite clear why Professor Hale calls the dark patches *dark calcium* or *dark hydrogen*, as in these parts calcium and hydrogen respectively are, according to the very principle of the spectroheliograph, shown to be *absent*."

In my understanding of the principle of the spectroheliograph, the instrument is quite as capable of recording defect of radiation as excess of radiation, i. e.; absorption phenomena are not less within its province than radiation phenomena. The spectroheliograph, according to this view, does not show that calcium or hydrogen are necessarily absent from any part of the solar disk. It simply indicates the existence of brighter or darker masses of these gases in certain regions. Thus, the dark flocculi shown on the disk, when the hydrogen line is employed, probably represent the higher and cooler masses of hydrogen gas seen in projection against the hotter and more uniformly diffused hydrogen in the lower chromosphere. Calcium vapor may also rise to a considerable height and cool to a temperature below that of the calcium vapor diffused throughout the lower chromosphere. Such a mass of vapor, if registered with a spectroheliograph of sufficient dispersion to permit photographs to be taken with the H_3 or K_3 line, would doubtless appear as a dark calcium flocculus. At present such objects are somewhat rare, since H_3 and K_3 are usually very narrow lines. Nevertheless, an illustration of a dark calcium flocculus, photographed with the spectroheliograph, is given in our paper.

I am therefore unable to agree with Dr. Lockyer's view, "that the regions where calcium exists correspond to those regions where hydrogen is absent." The known association of calcium and hydrogen in the chromosphere and prominences would seem to me to render such a

view very improbable, even if there were no other reasons against it. *Bright* hydrogen flocculi, in most cases easily distinguishable as such on the original negatives (but much less satisfactorily in the reproductions), are frequently found in disturbed regions, usually in the vicinity of sun-spots. *Dark* hydrogen flocculi, representing the absorption of comparatively cool hydrogen (probably, in most cases, at considerable altitudes) usually resemble, in general outline, the *bright* calcium flocculi in the same regions of the solar disk. As soon as it becomes possible to photograph with the H_3 or K_3 line, I think it probable that *dark* calcium flocculi, corresponding to the higher levels, will be frequently found in association with *dark* hydrogen flocculi. It will, of course, be understood that the term "flocculus," since it is used only to designate objects photographed in projection, does not, in itself, make any attempt to distinguish low-lying vapors from those immediately above them.

I am indebted to Dr. Lockyer for his article, and regret that I failed to make my meaning clear.

I wish I could conscientiously accept the compliment paid me by M. Deslandres, in ascribing to himself and to me the discovery of the flocculi in 1892. It is a well-known fact, however, that Professor Young, many years before, observed visually reversals of the H and K lines in the vicinity of sun-spots, and that Rowland and Jewell photographed these reversals before such investigations were undertaken by M. Deslandres and myself. I am sure that M. Deslandres will agree with me that the further records of this early work should also be accurately preserved, and that the photography of the *spectra* of flocculi should not be confused with the photography of their *forms* with the spectroheliograph. Since M. Deslandres has referred again to the history of the spectroheliograph, I may perhaps be pardoned for giving an outline of the facts. The spectroheliograph was first successfully employed in photographing the forms of flocculi at the Kenwood Observatory in the beginning of 1892, and Mr. Evershed constructed and used a spectroheliograph not many months later. In 1893 M. Deslandres obtained his first results with a spectroheliograph. In 1894, with a spectroheliograph having only a single prism, M. Deslandres made photographs of the solar disk with the second slit set on some of the dark lines. The images obtained in this way

are considered by M. Deslandres to represent the vapors in the reversing layer which correspond to the dark lines employed. He thus clearly recognized the principle which we have used in our more recent work; but his opinion as to the dispersion necessary in such work differs very widely from my own. Feeling certain that photographs obtained in this way, with an instrument of low dispersion, could not be depended upon to show anything more than the faculæ themselves (which can also be photographed by setting the second slit on the continuous spectrum), I did not think it worth while to make experiments in this direction until a suitable instrument should become available. The discovery of the dark hydrogen flocculi, and the results we have obtained with various lines of iron and other substances, are the natural consequence of employing dispersion sufficient to cause the dark line to cover completely the second slit. As I have always lacked confidence in experiments of my own with low dispersion, I have naturally felt that M. Deslandres stood equally in need of more powerful apparatus.

The paper of Professor Julius raises some questions of great interest, which I am not yet prepared to discuss in detail. While I think it possible that anomalous dispersion may ultimately prove to have a bearing on certain classes of solar phenomena, I have a strong belief in the objective existence of the photosphere, faculæ, spots, chromosphere, flocculi, prominences, and corona. On some other occasion I hope to have an opportunity to discuss the more general questions in the theory of Professor Julius. At present I confine myself to brief remarks on certain points raised in his discussion of the results obtained with the spectroheliograph.

The H_2 and K_2 lines are ascribed by Professor Julius, not to strongly radiating calcium vapor, but to light of nearly the same wave-length which has undergone anomalous dispersion in passing through a "tubular structure" containing calcium vapor. This explanation requires "that the brightness of the calcium flocculi must, as a rule, increase as the monochromatic light in which the Sun is photographed approaches the true absorption line." As a matter of fact, the *relative* brightness (contrast) of the flocculi increases as the slit is moved nearer H_2 or K_2, but their absolute brightness diminishes, so that longer exposures become necessary in successive

settings of the slit. In order that the contrast may increase, it is therefore necessary to suppose that the background decreases in brightness more rapidly than the flocculi.

The theory of anomalous dispersion requires, according toProfessor Julius, "the bright and dark structure generally to appear coarser and more woolly as the spectroheliograph is adjusted for kinds of rays that are more liable to anomalous dispersion"—i. e., as the second slit is moved toward the center of H_1 or K_1. As a matter of fact, however, it is mainly the larger flocculi that show such an effect, which we have attributed to expansion at higher altitudes. The finest and sharpest details ever recorded on our photographs were obtained with the H_2 line.

According to the theory of anomalous dispersion, the appearance of dark flocculi "is a direct consequence of the fact, that the particular distribution of the light in the solar image is not produced by local absorption and emission, but by irregular ray-curving. The rays are only caused to change their places; so an excess of light in the bright flocculi must necessarily be counterbalanced by a deficit in the surroundings." I do not think that a careful study of our original negatives would bear out this view, especially in the case of H_1 and K_1 photographs.

In my opinion, as already stated, the dark hydrogen flocculi are due to the absorption of comparatively cool hydrogen gas in the upper chromosphere and prominences. Professor Julius accounts for their darkness on the ground that "the ray-curving in the solar gases must generally be less with waves belonging to those narrower dispersion bands than with waves lying near the centers of the broad H and K bands." If "ray-curving" is a factor, and if the reasoning here is consistent with that in the first part of Professor Julius' paper, there remains the difficulty that the still narrower lines of iron and other substances give *bright* instead of dark structures.

Without further discussion, for the present, of Professor Julius' interesting paper, I can only say that our working hypothesis, though admittedly weak in some particulars, appears to me decidedly preferable to an explanation based wholly on the idea of anomalous dispersion. However, the possibility that anomalous dispersion may

in some degree affect results obtained with the spectroheliograph must not be overlooked in future work with this instrument.

While retaining our working hypothesis, I do so with full consciousness of its defects, and with a strong desire to remedy them, either by completing the present explanation, or by substituting a better general view, if such can be found.

MOUNT WILSON,
February 1905.

DISPERSION BANDS IN ABSORPTION SPECTRA[1]

By W. H. JULIUS

The appearance of absorption lines depends on various circumstances. As to the absorption phenomena in gases and vapors, such conditions as temperature, density, pressure, velocity in the line of sight, intensity and direction of magnetic field, have been fully studied and discussed. In the present paper we purpose to show that anomalous dispersion in the absorbing gas is also, to a great extent, accountable for certain typical features of the dark lines.

An originally parallel beam of light, when passing through a mass of matter the density of which is unequally distributed, will not remain parallel, and, generally speaking, the greatest incurvations will be noticed in those rays for which the medium has refractive indices differing most from unity; i. e., in those which, in the spectrum, lie closest to the absorption lines on either side. These particular kinds of light, while diverging into space, will spread in many more different directions than the average waves, and, as a rule, a smaller portion of them will fall into the spectroscope than of waves with refractive indices nearer to unity.

Accordingly, there must always be certain places in the absorption spectrum from which light is absent owing to dispersion in the absorbing vapor, for it may be taken for granted that the latter is never absolutely homogeneous. These darker parts in the spectrum we shall call *dispersion bands*. It stands to reason that these bands will overlap the regions of real absorption; so they might easily be mistaken for strengthened absorption lines, which no doubt has often been done.

We will now look somewhat more closely into the characteristics by which dispersion bands may be distinguished from absorption bands.

The curvature of a ray of light of a definite wave-length, at any point of a non-homogeneous medium, not only depends on the gradient

[1] A paper presented at the meeting on May 28, 1904, of the Royal Academy of Sciences of Amsterdam.

of optical density at that particular spot, but also on the angle which the beam makes with the levels of equal density. Its divergence will be the greatest when this angle is zero.

Strong ray-curving through anomalous dispersion in vapors may, therefore, be artificially produced in two ways: first, by using masses of absorbing vapor, presenting in a small space considerable differences in density, e. g., such as occur in the electric arc;[1] secondly, in larger spaces where the density varies but moderately, by making the light travel over a considerable distance under small angles with the levels of equal density.

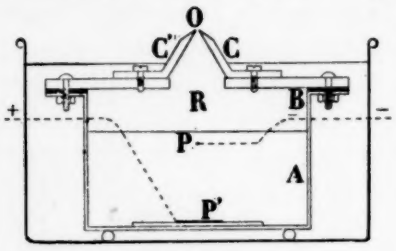


FIG. 1

I have chosen the latter method of investigation, especially on account of the extensive use which may be made of the phenomena presenting themselves, by applying them to the interpretation of numerous peculiarities of the spectra of celestial bodies.[2]

The absorbing medium was a Bunsen flame, of a peculiar shape, containing sodium vapor, and so arranged that the introduction of the salt could be easily regulated.

Fig. 1 represents a section of the burner. *A* is a copper trough, 80 cm long, 8 cm wide and 5 cm deep, thickly coated with varnish and having a broad flange. The planed brass plate *B* is firmly screwed upon the flange, and a leather packing makes the joint air-tight. On this cover, which has a rectangular opening 75 cm long and 2 cm wide, are fixed two brass rulers, *C* and *C'*, 75 cm long. They are so adjusted that at *O* they form a slit, having an exactly

[1] H. Ebert, "Wirkung der anomalen Dispersion von Metalldämpfen," Boltzmann *Festschrift*, p. 448.

[2] The abnormal solar spectrum of Hale; the peculiar distribution of light in several of the Fraunhofer lines, even in normal conditions; the variations in the average appearance of the spot spectrum accompanying the eleven-year period. All these phenomena have been easily explained from the considerations here alluded to (see W. H. Julius, *Astrophysical Journal*, **18**, 50–64, and *Proc. Roy. Acad. Amst.* **5**, 589–602; 662–666; **6**, 270–302).

The present investigation is a continuation of the experiments with the long sodium flame, a short account of which has already been given on those former occasions in support of our theory.

uniform width of about 0.1 cm over the whole length. The prismatic space between C and C' is closed at each end by a small triangular brass plate. The trough is filled to a certain height with a saturated solution of soda, and into the remaining space a mixture of illuminating gas and air is conveyed by means of tubes, entering at both ends. These tubes are fed from a mixing bottle in which the gas and the air are being driven through two separate regulating taps.

If now the flame were left to burn without any further precautions, the slit O would soon be closed in consequence of the one-sided heating of the rulers. It was therefore found necessary to place the trough in a vessel with running water, reaching up to the burner. In this way a uniform and steady flame was obtained.

A few millimeters below the level of the salt solution a platinum wire P is stretched over the whole length of the lamp. Its ends are soldered to insulated copper wires, which pass through the walls of the trough, and are connected to the negative pole of a storage battery of 20 volts. From the positive pole two insulated wires lead to the ends of a long strip of platinum P', which rests on a glass plate at the bottom of the trough. As soon as the circuit is closed, innumerable minute particles of the fluid rise into the space R, and cause the flame to emit a beautiful, clear, and constant sodium light, the intensity of which can be controlled and regulated by means of an ammeter and a variable resistance.

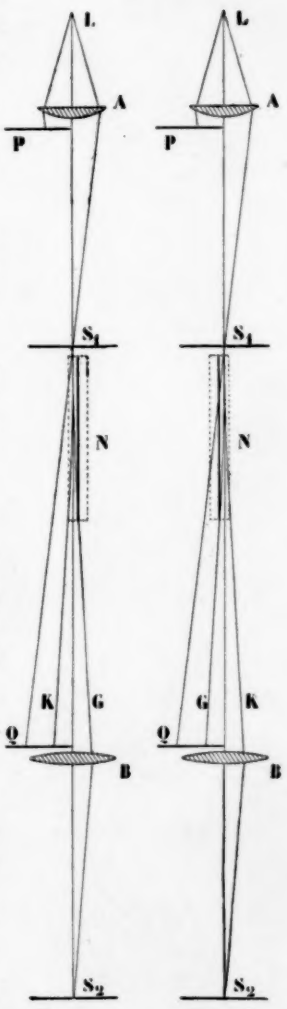


FIG. 2*a* FIG. 2*b*

In Fig. 2, *a* and *b*, are shown two different ways in which the light travels through this long sodium flame. L represents the crater of

an electric arc of 20 amperes. The lens A throws an image of the crater on the slit S, which, in its turn, is depicted by the lens B on the slit S of a grating spectroscope.

About half of the conical beam of light which leaves A is intercepted by the screen P, and the part which the slit S_1 allows to pass falls almost entirely on the screen Q, which has been shifted so close to the optical axis of both lenses that only a narrow streak of light can reach the slit S_2, through the middle of B. The large gas burner stands on a horizontal slide, which is movable up and down and around a vertical axis; thus, by means of screws, it can easily be put in any position required.

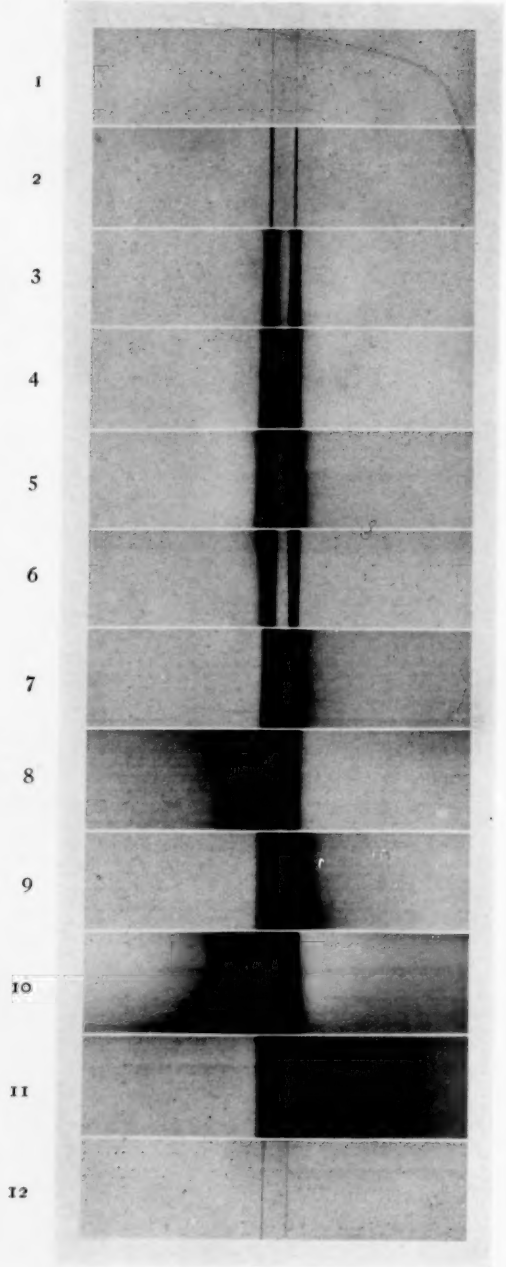
When the axis of the flame (which we assume to be in its most luminous part, i. e., a little above the blue-green core) coincides with the optical axis of the system of lenses, both the D lines will be seen symmetrically widened in the spectroscope. If not perfect, the symmetry will easily be corrected by slightly shifting the screens P and Q.

No. 1 of Fig. 3 (Plate XV) refers to the case when the flame N is not burning; the narrow absorption lines are due to traces of sodium surrounding the carbon points. When the flame is burning, a very weak current passing through the sodium solution will produce the effect shown in 2. The photographs 3, 4, and 5 were obtained with currents of about 1, 3, and 6 amperes, the flame always being in the symmetrical position.

We will now examine the case represented by Fig. 2, *a*. Here the axis of the flame has been shifted 3 mm toward the right. The narrow beam of light which reaches S_2 penetrates only that part of the flame where the density of the sodium vapor *increases* from left to right. In a structure of this kind waves for which the vapor has a great index of refraction deviate toward the right, e. g., S_1G. They are not intercepted by Q, and consequently reach the slit S_2. In fact, the presence of the sodium vapor allows similar waves to enter that slit even in larger quantity than they would do without it, for rays of this kind, issuing from the uncovered half of A, which if traveling in a straight line would be intercepted by Q, can, when refracted, penetrate the lens B.

The case is entirely different for those kind of rays for which

PLATE XV



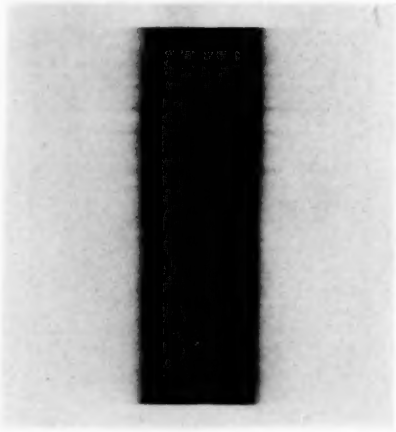


FIG. 3 FIG. 4

DISPERSION BANDS IN THE ABSORPTION SPECTRUM OF SODIUM

sodium vapor has refractive indices that are smaller than unity. Such rays deviating toward the left (as shown in S_1K) are intercepted by Q, and consequently will be absent from the spectrum.

Nos. 6, 8, and 10 are reproductions of photographs taken under these conditions. On the left are seen the smaller, on the right the greater, wave-lengths (in fact, in the whole series of photographs the stronger D line appears on the left side); so it is obvious that really the waves lying on the red-facing side of the D lines—i. e., those for which the vapor has high refractive indices—are *strengthened* by anomalous dispersion; and that, on the other hand, the waves on the violet side have been considerably *weakened*.

Alternately with 6, 8, and 10 the photographs 7, 9, and 11 were taken. The position of the flame was now as indicated in Fig. 2, *b*, i. e., its axis had been shifted 3 mm to the left, so that the central beam had to traverse that part of the flame where the density of the sodium vapor *decreases* from left to right. Here we notice that the rays with low refractive indices deviate toward the right and that a larger number of them reach the slit S_2, e. g., S_1K, while the rays with high refractive indices, such as S_1G, are intercepted by Q.

Nos. 6 to 11 show the effect of a gradual increase in the density of the sodium vapor. In No. 12 we again notice the sharply defined sodium lines after the flame has been extinguished at the end of the series of experiments; they are somewhat stronger than those at the beginning of the series, because much sodium vapor had spread through the room during the operations.

When carefully examining the original negatives it is possible in most of them to distinguish the rather sharp central absorption lines from the overlying dispersion bands (especially in the photographs obtained when the position of the flame was symmetrical; the reproductions fail to bring out this peculiarity). Advantage has been taken of this fact in so arranging the twelve photographs here reproduced that equal wave-lengths occupy corresponding places. Then it is seen that the "centers of gravity" of the two dark bands, as well as the brighter space between them, have been alternately shifted to the left and to the right—a phenomenon which needs no further explanation.

As a matter of course, the interposed flame causes the illumination in the plane of the slit S_2 to be very irregular, especially with regard

to those radiations undergoing anomalous dispersion in the vapor. It is evident that some kinds of rays which are absent from one part of that plane will be found in excess at another. The distribution of light in this irregular field of radiation might be explored by moving S_2, together with the spectroscope, within it. The same object can be obtained with less trouble by means of a thick piece of plate glass, mounted vertically between B and S_2 in such a manner that it may be moved around a vertical axis. When turning it a little we make the whole radiation field beyond the plate glass shift parallel to itself, thus causing other parts to cover the slit. This influences the aspect of the dispersion bands very materially. In certain positions apparent emission lines of sodium vapor may happen to be seen, which disappear as soon as the arc-light at S_1 is intercepted.[1]

In conclusion we wish to draw attention to a peculiarity we repeatedly observed in the dispersion bands. The dark shading in a dispersion band does *not* become deeper in proportion as we approach nearer to the central absorption line, but seems to reach its maximum obscurity at certain, though not always equal, distances on both sides of the center; while in the space between, the light appears somewhat intensified, just as if a wide absorption band had been partly covered by a narrower emission band, the center of which is again occupied by the fine absorption line. This phenomenon cannot, however, be attributed to radiation emitted by the absorbing sodium flame: for in our arrangement the intensity of the emission from the flame could bear no comparison with that of the arc for corresponding waves. In order to make sure, we tried to photograph the emission spectrum of the flame, exposing the plate during the same length of time and under the same conditions as had been done for obtaining the absorption spectrum; but not a trace of any impression could be detected on the photographic plate.

The light on both sides of the central line therefore originates in the carbon points, and this we explain on the principle of ray-curving. The kinds of rays which are most strongly refracted in the flame may, under certain conditions, be curved twice, or even more times, when passing nearly parallel to the system of the levels of

[1] These bright lines originate in the same manner as the light of the chromosphere. The chromospheric lines are not emission lines, but "bright dispersion bands."

equal density (in the manner described on a former occasion[1]), and will therefore have a greater chance of reaching the slit S_2 than rays which are less strongly curved. The relative intensity with which the waves belonging to those central parts of the dispersion bands appear in the spectrum increases with the distance over which the light has traveled along such a lamellar or tubular structure. Should the true absorption line happen to be exceedingly narrow, the dispersion band may give the impression of a double absorption band, which need not be symmetrical. In Fig. 4 on the plate is reproduced an enlargement of one of the photographs obtained by an almost symmetrical position of the flame.

We hold that the dispersion bands play an important part in many of the well-known spectral phenomena, such as the widening, shifting, reversal, and doubling of lines. In a subsequent communication I purpose to examine from this premise various phenomena observed in the spectra of variable stars and other celestial bodies.

[1] *Proc. Roy. Acad. Amst.* **5**, 596; *Astrophysical Journal*, **18**, 58, 1903.

SPECTROHELIOGRAPHIC RESULTS EXPLAINED BY ANOMALOUS DISPERSION

By W. H. JULIUS

It is not surprising that the scientific world should be highly interested in the beautiful results obtained by Hale and Ellerman with the spectroheliograph.[1] The brilliant method elaborated and applied by these investigators enables us to see at a glance, as well as to study in minute details, how the light of any selected wave-length was distributed on the total solar disk at any given moment. W. S. Lockyer, in giving an abstract from the paper here alluded to in *Nature*, No. 1800, rightly entitles it "a new epoch in solar physics." Indeed, the spectroheliograph proves capable of providing us with an abundance of new information, which other existing methods could never give, and the value of which will remain, whatever may be the ideas on the Sun's constitution derived from it.

But, nevertheless, even the most splendid collection of new facts is useless so long as we have no theoretical ideas connecting them with achieved knowledge. Hale and Ellerman, accordingly, in describing the observed phenomena, lay down quite definite conceptions regarding certain conditions and configurations of matter in the solar atmosphere, by which the observed distribution of the light in the image of the Sun is assumed to be produced. In the cited publication they put forth the working hypothesis that the "calcium flocculi," or bright regions showing themselves all over the image of the Sun when it is photographed in so-called calcium light, are columns of calcium vapor rising above the columns of condensed vapors of which the photospheric "grains" are the summits.[2] This hypothesis, though at first proposed mainly as a guide to further research,[3] has been subsequently[4] employed by the same authors with much

[1] G. E. Hale and F. Ellerman, "The Rumford Spectroheliograph of the Yerkes Observatory," *Publications of the Yerkes Observatory*, **3**, Part I, 1903.

[2] *Ibid.*, p. 15. [3] *Ibid.*, p. 13.

[4] G. E. Hale and F. Ellerman, "Calcium and Hydrogen Flocculi," *Astrophysical Journal*, **19**, 41–52, 1904.

less restriction as the basis on which the photographs ought to be interpreted.

The great authority of Hale and of such critics as W. S. Lockyer, J. Evershed, and others who, in abstracts from the work of Hale and Ellerman, concur in most of the interpretations there given, might cause the value of those ideas to become overestimated and extended beyond the original intention of the authors.

It is not superfluous, therefore, to show how we may quite as well account for all the new phenomena thus far revealed by the spectroheliograph, if we start from the entirely different conceptions of the Sun's constitution which the consequences of ray-curving in non-homogeneous media and of anomalous dispersion of light in absorbing vapors have suggested to us.

Both these circumstances are left absolutely out of consideration by Hale and Ellerman. Their conclusions are all founded on the erroneous supposition that the monochromatic light by which their images of the Sun are photographed has traveled from the source in straight lines, and that they are right, accordingly, in supposing light-emitting masses of calcium vapor to exist in the exact directions, along which calcium radiations seem to reach us. In making this supposition they fall into the same error as one who would assume the refracting facets of the crystal globe of a burning lamp to be independent sources of light.

Our new explanation of the spectroheliographic results will be founded on the hypothesis that the Sun is an unlimited mass of gas in which convection currents, surfaces of discontinuity, and vortices are continually forming under the influence of radiation and rotation, so that the various composing elements are mingled as completely as nitrogen and oxygen in the Earth's atmosphere.[1] This hypothesis too will, of course, want modification in the light of future results; but for the present it seems, so far as the visible phenomena are considered, not to clash with any observation or physical law.

The irregular motion of electrons in the deeper layers of the Sun, where the density is very great, gives rise to the radiation with a continuous spectrum. We shall take only *this* radiation into account.

[1] A sketch of a solar theory, based on this hypothesis, is to be found in the *Revue générale des Sciences*, **15**, 480–95, May 30, 1904.

Peculiar radiations, emitted by the more rarefied outer parts of the gaseous body and giving a bright-line spectrum, may perhaps add a perceptible quantity of light to the bulk, but this selective emission, if present, does not play any part in our explanations. So we behold the brilliant core of the Sun through an extensive envelope, consisting of a transparent but selectively absorbing mixture of gases, into which the core gradually spreads. It stands to reason that the average density of this envelope slowly decreases in the direction from Sun to Earth; but at right angles to that direction the density must be in some places much more variable. For it is a minimum in the axes of vortices; and the average direction of the whirl-cores, lying between the Earth and the central parts of the Sun in the surfaces of discontinuity, differs but little from our line of sight. The rays of the Sun thus reach us after having traveled a great distance along lines making small angles with the levels of slowest density variation in a lamellar, partly tubular, structure.[1]

Under these circumstances the solar rays will be sensibly incurvated on their way through the envelope, especially those suffering anomalous dispersion. As a rule, beams consisting of the latter kinds of rays will show an increased divergence; they will reach the Earth with less intensity than the normally refracted light, and so will give rise to dark *dispersion bands*[2] in the solar spectrum. And the degree of divergence will not only be different with waves which in the spectrum are found at different distances from the absorption lines, but it is also clear that the divergence with which various beams of *any definite* kind of light arrive at the Earth must differ largely according to the dioptrical properties exhibited along the paths of those beams by the system of surfaces of discontinuity.

The foregoing inferences really imply the whole of our interpretation of the results thus far obtained with the spectroheliograph. This we shall show by amply discussing some of their main features.

The broad dark bands, designated by Hale and Ellerman as H_1 and K_1, are not absorption bands, but dispersion bands. Real

[1] For considerations which have induced us to hold that a similar structure of the Sun is very probable, I refer to former publications: *Proceedings of the Royal Academy of Amsterdam*, **5**, 162–71, 589–602; **6**, 270–302.

[2] W. H. Julius, "Dispersion Bands in Absorption Spectra," *ibid.*, **7**, 134.

absorption by the solar calcium vapor we hold to be restricted to the central dark lines H_3 and K_3. The bright bands H_2 and K_2, predominating in the spectrum of the "flocculi," and attributed by Hale and Ellerman to strongly radiating calcium vapor, result in our theory from the fact that with beams of light the wave-length of which is very near to that of the central absorption lines, the divergence may be diminished, or even changed to convergence by the tubular structure. Indeed, such rays deviate more strongly than those standing farther from the absorption lines; and as soon as they undergo more than one incurvation, they have a chance of reaching the Earth with increased intensity. This chance improves in proportion as the index of refraction departs from unity, be it in a positive or in a negative sense.[1] We conclude from it that the brightness of the calcium flocculi must, as a rule, increase as the monochromatic light in which the Sun is photographed approaches the true absorption line.

This consequence of our theory exactly corresponds to one of the chief peculiarities, which immediately struck Hale and Ellerman on inspecting sets of photographs taken at short intervals of time with the second slit in different positions within the H and K bands. In order to account for the same fact, those investigators are obliged, by their working hypothesis, to suppose that in higher regions of the Sun's atmosphere the calcium vapor radiates more strongly than in lower levels. This cannot be called a very satisfactory inference, the less so since the supposition is added that the incandescent vapor is rising from much deeper layers and, therefore, considerably expanding—a process during which, according to our physical notions, the temperature must fall. Here we meet with a serious difficulty; Hale and Ellerman try to get rid of it by means of the rather vague assumption that some electrical or chemical effect may be responsible for the bright radiation emitted by this calcium layer, which is intermediate between two absorbing layers.[2]

Our theory can dispense with such additional hypotheses.

Another characteristic peculiarity, observed in every series of photo-

[1] In the experimental investigation on dispersion bands, before mentioned, this brightening in the middle of the dark bands has been distinctly observed. Cf. also *Proceedings of the Royal Academy of Amsterdam*, **5**, 596.

[2] *Astrophysical Journal*, **19**, 44, 1904.

graphs taken at short intervals with the slit set at various points on the broad H and K bands, is the following. When the slit is set, e. g., at a remote point of K_1, the structure of the solar image appears relatively fine, sharp, and detailed. Approaching the central line, we see some of the brilliant spots vanish. Others grow more extensive, especially those lying in the vicinity of sun-spots; at the same time their outlines become less sharp, so that finally the whole image gives us the impression of a coarser, and at the same time a more woolly, structure.[1]

Hale and Ellerman hold that the successive photographs refer to gradually higher levels, and conclude that the masses of calcium vapor must have a tree-like shape. W. S. Lockyer, in *Nature*, No. 1800, draws a scheme showing this conception.

Against this interpretation we propose the following one:

The amount by which the divergence of a beam of light is altered in consequence of the presence of calcium vapor in the streaming and whirling mass depends of course, on the proportion of calcium in the mixture, and, besides, on two other circumstances: (1) the position occupied in the spectrum by the selected kind of light with regard to the absorption lines, and (2) the steepness of the density-gradients in the mixture along directions perpendicular to the path of the beam.

Let us suppose the selected light to correspond to the extreme edge of H_1 or K_1, then its index of refraction differs but little from unity. Accordingly, very considerable inequalities of density are required to cause a perceptible change in the divergence of such beams. Similar great inequalities may indeed occur at many separate places, but at each of them they cannot, of course, extend very widely. This accounts for the fine and rather sharply defined reticulation shown by the so-called "low-level" photographs.

If the second slit were set a little nearer to the center of the line, the distribution of the light in the solar image would at all events differ considerably from that of the former case; for, the indices of refraction being very different for neighboring waves within a dispersion band, the divergence of beams, starting from the same point of the Sun, must vary largely with the wave-length. Thus it is clear that

[1] Such series of photographs are reproduced in *Publications of the Yerkes Observatory*, **3**, Part I, Plates V, VI, X, XI, XII, XIII.

bright or dark spots, visible on one photograph, may be wanting in the other.

Moreover, the general character of the image must change as we approach the central line; for in proportion as the indices of refraction depart from unity, slower variations of density suffice for producing sensible differences of divergence; and, as a matter of course, in any whirling region slightly inclined density-gradients will take up larger spaces than very steep ones. Besides, when the second slit of the spectroheliograph, having a given width, is set near to the central absorption line, the wave-complex which it allows to pass covers a greater variety of refractive indices than when it is set farther from the central line. In the former case the distribution of the light in the solar image must, therefore, be less differentiated. Both circumstances co-operate in causing the bright and dark structure generally to appear coarser and more woolly in proportion as the spectroheliograph is adjusted for kinds of rays that are more liable to anomalous dispersion.

From the same point of view it is not surprising that on photographs taken in H_2 or K_2 light the calcium flocculi are particularly bright and extensive in spot regions; for in such regions the "tubular" structure of the gaseous mass, by which the strongly curved rays are kept together and conducted, is most developed.

Hale and Ellerman also mention "dark calcium flocculi,"[1] which they describe as special objects, visible in so-called "high-level photographs," and not to be confounded with the general dark background produced by the absorbing vapor of deeper layers. Dark flocculi often surround the large bright flocculi of spot regions, as is shown, e. g., in Fig. 4, Plate V, of the cited publication. The explanation given by them is that we might have here some indications of the cooler K_3 calcium vapor, which rises to a considerably greater height than the K_2 vapor of the bright flocculi.

In our theory the presence of these darker regions is a direct consequence of the fact that the particular distribution of the light in the solar image is not produced by local absorption and emission, but by irregular ray-curving. The rays are only caused to change their places; so an excess of light in the bright flocculi must necessarily be counterbalanced by a deficit in the surroundings.

[1] *l. c.*, p. 19.

H and K are by far the broadest bands of the visible solar spectrum; even with moderate dispersion the second slit of the spectroheliograph could easily be set at different points within these bands. When the dispersion of the instrument was increased by means of a grating, photographs of the Sun could be obtained with light falling entirely within a widened line of hydrogen or of iron.

Photographs made with H_β or H_γ light showed also a flocky structure, differing, however, materially from that obtained with H and K. Hale and Ellerman therefore assume dark and bright clouds of hydrogen to exist in the solar atmosphere. Upon the whole, but not in the details, the hydrogen flocculi correspond in form and position to the calcium flocculi photographed with H_2 or K_2 light; the general aspect of the photographs is fainter, they show less contrast, and the detailed structure observed in H_1 or K_1 light is wanting. The most striking fact, however, is that *the bright calcium flocculi of the H_2 or K_2 photographs are replaced on the H_β photograph by dark structures of similar form.* Only in a few places in the vicinity of sun-spots small *bright* hydrogen flocculi occur which coincide with parts of bright calcium flocculi.

Hale and Ellerman hardly make an attempt to explain these facts which, in the light of their working hypothesis, are really puzzling.

We get a much clearer view of the matter as soon as we suppose the widening of the hydrogen lines also to be produced by anomalous dispersion, instead of by absorption only.

Indeed, the ray-curving in the solar gases must generally be less with waves belonging to those narrower dispersion bands than with waves lying near the centers of the broad H and K bands. Even in the powerful whirls of spot regions there will only sporadically be found places where the tubular structure is sufficiently marked to keep together rays belonging to the dispersion bands of hydrogen in the same way as it does gather the strongly curved H_2 and K_2 light in the large, bright calcium flocculi. Accordingly, we shall meet with very few places in bright calcium flocculi where the photographs in H_β or H_γ light also exhibit brilliant points. All the rest of the bright H_2 and K_2 regions correspond to those parts of the gaseous mass where the differences of density, though not so excessive, are nevertheless very considerable; but whereas in that structure the H_2 rays are

repeatedly curved and may be made to converge, the less strongly incurvated H_β rays will in the same regions diverge and be dissipated in a considerable degree, thus giving rise to dark places in the photographs. Outside the bright calcium flocculi, finally, where the H_2 and K_2 photographs are dark in consequence of increased divergence of the beams, no strong incurvation is given to the H_β or H_γ light. At those places the image of the Sun, photographed in hydrogen lines, must therefore be less dark.

The rather faint character of the hydrogen flocculi, and the absence of sharp outlines and of strong contrasts in the structural elements, we ascribe to the dispersion bands of hydrogen being relatively narrow and so allowing rays with a great variety of refractive indices to pass simultaneously through the second slit of the spectroheliograph. The hydrogen photographs, too, would show finer details, like those in K_1 light, if the dispersion of the apparatus were still greater and the second slit still narrower.

We believe that we have shown that every peculiarity thus far noticed in the photographs obtained with the spectroheliograph may easily be deduced from the same fundamental hypothesis regarding the constitution of the Sun which has already proved capable of giving a coherent interpretation of the solar phenomena known before. Not a single new hypothesis was required.

DISPERSION BANDS IN THE SPECTRA OF δ *ORIONIS* AND *NOVA PERSEI*[1]

By W. H. Julius

When light, giving a continuous spectrum, passes through a selectively absorbing, non-homogeneous mass of gas, the spectrum of the transmitted light contains places which, according to circumstances, may contrast as bright or as dark regions with their surroundings.[2] Though resembling emission and absorption lines, these bands have a wholly different origin. They are due to anomalous dispersion and, therefore, the name *dispersion bands* has been suggested for them.[3]

Dispersion bands always appear in the proximity of absorption lines, covering them more or less symmetrically; they show great variety in width and strength, and the distribution of the light in them may be irregular, so as to give the impression that one is witnessing cases of shifting or doubling or complicated reversal phenomena of widened absorption lines. All these cases can be produced almost at pleasure in the absorption spectrum of sodium vapor by merely varying the structure of the non-homogeneous medium through which the light is made to travel.

In the spectrum of the various parts of the solar image dispersion bands play an important part.[4] We can scarcely doubt that they are also present in stellar spectra; for the light coming from the stars must, as a rule, have traveled through immense gaseous envelopes and suffered ray-curving and anomalous dispersion, just as well as the light from the Sun.

Taking for granted that most of the visible stars are *rotating* gaseous bodies, with or without a solid core, we must suppose them to have a structure, describable by surfaces of discontinuity with

[1] A paper presented at the meeting on October 29, 1904, of the Royal Academy of Sciences of Amsterdam.

[2] *Proc. Roy. Acad. Amsterdam*, **2**, 580, 1900; *Astrophysical Journal*, **12**, 191, 1900.

[3] *Proc. Roy. Acad. Amsterdam*, **7**, 134–140, 1904.

[4] *Ibid.*, 140–147, 1904.

waves and vortices, and resembling the peculiar structure of the Sun, by which it has proved possible to explain solar phenomena.[1] Consequently, the stars too give existence to "irregular fields of radiation" rotating with them. Our line of sight continually cuts other parts of the refracting mass; it may pass closely along surfaces of discontinuity, now on the one, now on the other side of them; so the light reaching us must vary in strength and in composition.

The variability of many stars is very likely to result from this cause; and from the same principle it necessarily follows that their spectral lines should be liable to every kind of change in place and in appearance.

In many cases where the application of Doppler's principle leads to very unsatisfactory conclusions, the dispersion bands afford a plain solution. Let us consider, for instance, the spectrum of δ *Orionis*.

In this spectrum rapid changes in the position of the lines had been observed by Deslandres (1900), who concluded from them that δ *Orionis* was a spectroscopic binary having a revolving period of 1.92 days. Some observations made by J. Hartmann[2] did not agree with this period. Professor Hartmann therefore submitted the star to an extensive spectrographic investigation in the winter months of 1901–2 and 1902–3, and, from the forty-two plates obtained, drew the following conclusions:

The spectrum contains chiefly the lines of hydrogen and helium; besides a few belonging to silicium, magnesium, calcium.

The calcium line at λ 3934 (corresponding to K of the solar spectrum) is extraordinarily weak, but almost perfectly sharp; all the other lines (nineteen in number) are very diffuse and dim, often appear crooked and unsymmetrical, sometimes indeed double. While every prepossession of the observer was most strictly avoided during the measurements, it was found that the centers of the diffuse lines really oscillate, the period being 5.7333 days; but, owing to the unsymmetrical appearance of many of the lines, no evidence could be obtained that the values of the displacements were in mutual

[1] *Ibid.*, **5**, 162–171, 589–602; **6**, 270–302, 1903.

[2] "Unterschungen über das Spectrum und die Bahn von δ *Orionis*," *Sitzungsber. der K. Preuss. Akad. d. Wissenschaften*, **14**, 527–542, March 1904.

agreement for all the lines on one and the same plate. From the average displacements Hartmann calculated the "variable velocity in the line of sight," and finally the elements of the orbit.

An utterly surprising result, yielded by the measurements, was *that the calcium line at λ 3934 does not share in the periodic displacements of the other lines*, but shows a constant shift corresponding to a velocity in the line of sight of +16 km (reduced to the Sun).

Hartmann rejects the idea that this line should have originated in the Earth's atmosphere; also the assumption that it belongs to the second component of the binary system. He is thus led to the hypothesis that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud of calcium vapor which recedes with a velocity of 16 km. By examining the spectra of neighboring stars no further information as to the existence of such a cloud was obtained.

A quite similar phenomenon, however, had been exhibited by the spectrum of *Nova Persei* in 1901: the lines of hydrogen and other elements were enormously broadened and displaced and continually changing their appearance, but during all the time the two calcium lines at λ 3934 and λ 3969, as well as the D lines, were observed as perfectly sharp absorption lines, yielding the constant velocity of +7 km. Hartmann therefore assumes that also in the line of sight between the Sun and *Nova Persei* there exists a nebulous mass consisting, in this case, of calcium and sodium vapor, and moving from the Sun at the rate of 7 km per second.

It must be admitted that these hypothetical clouds do not form a satisfactory solution of the problem.

A much simpler explanation of the phenomena may be derived from our conception of the irregular fields of radiation caused by the stars.

We need only suppose that the outer parts of δ *Orionis* and of *Nova Persei*, like those of so many other stars, contain much hydrogen and helium, little calcium and sodium. The currents and vortices in the gaseous mass, which produce the irregularities of the field of the star's radiation, bring about very broad dispersion bands in the vicinity of the lines of hydrogen, helium, etc. The darkest parts of these bands will be displaced when, by the star's rotation,

masses in which the density is variously distributed, pass our line of sight. The dispersion bands of calcium and sodium, on the other hand, are so narrow that the varying position of their darkest parts cannot be distinguished from the fixed position of the corresponding absorption lines. The constant displacement of the latter indicates that δ *Orionis* recedes from the Sun with a velocity of 16 km, *Nova Persei* of 7 km a second.

According to our opinion δ *Orionis*, therefore, is *not* a spectroscopic binary.

In the spectra of a great many stars oscillations and duplications have been observed only with diffuse lines. In those cases too the displacements are, as usual, expressed in so many kilometers a second, because no other interpretation than motion in the line of sight is thought of. From the above considerations it follows, however, that the observed oscillations are very likely to be executed by dispersion bands and not by the absorption lines; then no sufficient ground remains for classing such stars among spectroscopic binaries and for calculating orbital elements.

Several difficulties to which the conclusions derived from Doppler's principle lead us, will then disappear at the same time. How, for instance, are we to realize the physical conditions of the orbital motion in such so-called binaries as ι *Orionis*, 57 *Cygni*, θ^1 *Orionis* and many others, all of which are involved in nebulous matter, but whose motion in the line of sight is nevertheless—according to Frost and Adams—subject to periodical variations of 70, 90, 60 km a second, in spite of our physical notions concerning resistant media? When, on the other hand, the observed displacements of spectral lines, as well as the oscillations of the brightness of similar stars, are supposed not to result from motion in orbits, but from irregularities in their fields of radiation, there remains nothing astonishing in the fact that such variations often occur with stars involved in nebulosity.

In order to explain certain peculiarities in the spectra of *Novae* the principle of anomalous dispersion has already been applied by H. Ebert.[1] A characteristic of those spectra—viz., the presence of

[1] "Ueber die Spektren der neuen Sterne," *Astronomische Nachrichten*, **164**, 65, 1903.

double lines consisting of a bright and a dark component, the bright one being displaced toward the red, the dark one toward the violet—is very suggestively explained by this author in connection with the theory of Seeliger. According to this theory, the appearance of a *Nova* results from a dark or faintly luminous celestial body entering at a great velocity into a cosmic nebula. During this process the front part of the star's surface will become excessively heated and luminous, and a dense gaseous atmosphere will be formed, in which as Ebert shows, the incurvation of the rays must necessarily be such as to cause the dispersion bands appearing in the spectrum to be *bright* on the red-facing and *dark* on the violet-facing side of the absorption lines.

Ebert expresses the opinion that displacements and duplications of lines in the spectra of many variables of short period might be explained in a similar way, i. e., by admitting that the radiating power of such bodies is very unequal in different parts of their surface, and that they are surrounded by dense atmospheres. Their rotation will then cause us to see, as it were, the phenomena of the *Novae* periodically repeated.

In certain cases this interpretation may undoubtedly account for the peculiarities observed in the spectra of variables; nevertheless we cannot generalize the idea without meeting with some serious difficulties. First, it is not easy to form a clear conception of the physical conditions prevailing in a star, the incandescent surface of which is supposed to contain permanently large regions radiating very much less than the rest. The Sun with its spots may certainly not be adduced as an analogous case. Moreover, there are plenty of instances that in the spectrum of a variable, bright bands appear at the *violet* side, dark bands at the *red* side of the absorption lines, i. e., just the reverse of the phenomenon presented by the *Novae;* and it happens that with one and the same star bright and dark dispersion bands change places in course of time with respect to the average position of the absorption lines. This occurs, e. g., in the spectrum of *Mira Ceti*, as will appear when comparing the observations made by Vogel and Wilsing in 1896[1] with those made by Campbell in 1898[2] and by Stebbins in 1903;[3] also in the spectrum

[1] *Sitzungsber. der Berl. Akad.*, **17**. [2] *Astrophysical Journal*, **9**, 31. [3] *Ibid.*, **18**, 341.

of θ^1 *Orionis* observed by Huggins in 1894 and 1897,[1] etc. In those cases the explanation suggested by Ebert would require the addition of special hypotheses.

Our fundamental hypothesis, that the structure of most stars is similar to that of the Sun (it being admitted, of course, that the stars may greatly differ as to the extent of their respective gaseous envelopes, the average steepness of the density-gradients in them, their chemical composition, temperature, etc.), seems to admit of the interpretation of a greater variety of facts. It makes displacements of the dispersion bands toward the long and the short waves almost equally probable—if we leave the asymmetry in the form of the dispersion curves out of question and provisionally assume the directions of the axes of the stars to be distributed at random through space.

The direction in which we see a star may be regarded as a steady line in space, allowance being made for aberration and parallax. If, now, the distribution of the matter constituting that celestial body remains nearly unchanged for a long time, then after each rotation of the star our line of sight will again pass through the same points of the "optical system," and we shall observe an accurately periodical course in the star's brightness and in the appearance of its spectral lines. In most cases, however, currents and vortices will cause more or less considerable alterations to arise in the distribution of the density of the gaseous mass, and, consequently, in the composition of the beam of light reaching the Earth at a given phase of the star's rotary motion. Thus the strictly periodical succession of phenomena is open to any degree of disturbance. The very irregular and sometimes rapid changes in the brightness of objects like *o Ceti*, *SS Cygni*, *μ Cephei*, etc., are much more intelligible from this point of view, than from interpretations based on the assumption of violent eruptions, large spots, or eclipses caused by dark companions. And it is so difficult to make a sharp distinction between variables of long period and *Novae* that we should not resent the idea of comparing even the appearance of a new star to the sudden gleam of a revolving coast-light when the optical system, giving to the beam a considerable decrease in divergence, passes our line of sight.

[1] *An Atlas of Representative Stellar Spectra*, p. 140.

Minor Contributions and Notes.

STARS HAVING PECULIAR SPECTRA[1]

An examination of the photographs of the Henry Draper Memorial has led to the discovery, by Mrs. Fleming, of a number of variable stars and objects having peculiar spectra, in addition to those previously published. A list of these has been compiled by Mrs. Fleming, and is given below, together with a number of variables already known, for which the spectrum

PECULIAR SPECTRA

Constellation	*B. D.* No.	R. A. 1900	Dec. 1900	Magn.	Spectrum	Description
		h m	° ′			
Andromeda....	.....	0 10.8	+46 27	...	Md	Variable. *X Andromedae*
Andromeda....	+38°315	1 33.7	+38 50	...	Md	Variable. *Y Andromedae*
Taurus.....	.....	4 32.8	+ 8 9	...	Md	Variable
Orion.....	+ 7°768	4 53.6	+ 7 59	...	Md?	Variable. *R Orionis*
Orion.....	+ 4°949	5 25.1	+ 4 7	...	K 5 M	Variable. Peculiar
Camelopardalus...	.....	5 49.4	+74 30	...	Md	Variable. *V Camelopardali*
Monoceros.....	−11°1460	6 16.8	−11 44	5.9	B Pec.	*Hβ* bright
Monoceros ...	− 2°1581	6 17.7	− 2 9	...	Md	Variable. *V Monocerotis*
Ursa Major...	.....	8 33.9	+50 29	...	Md	Variable. *— Ursae Majoris*
Ursa Major...	+50°1603	8 56.2	+50 29	9.2	N	Peculiar
Virgo.....	− 5°3456	12 9.5	− 5 29	...	Md	Variable. *T Virginis*
Boötes.....	+14°2700	14 1.7	+13 58	...	Md?	Variable. *Z Boötis*
Libra.....	− 2°3939	14 58.8	− 2 28	9.6	N	Peculiar
Norma.....	−54°6651	15 36.4	−54 40	...	Md	Variable. *T Normae*
Lyra.....	+36°3066	18 11.5	+36 38	...	Md	Variable. *W Lyrae*
Hercules.....	.....	18 16.7	+31 41	...	Md	Variable
Sagittarius....	.....	18 29.5	−31 47	...	Pec.	Dark bands
Lyra.....	.....	18 42.2	+43 32	...	Md	Variable. *RW Lyrae*
Sagittarius....	−29°15574	18 52.4	−29 38	8.9	Pec.	Dark bands
Sagittarius....	.....	19 8.5	−19 0	...	.....	Variable
Sagittarius....	−33°14076	19 10.0	−33 42	...	Pec.!!	Variable. *RV Sagittarii*
Sagittarius....	.....	19 13.8	−21 7	...	Md	Variable. *Z Sagittarii*
Cygnus.....	+49°3225	20 9.8	+49 9	...	Mc 5 d	Variable
Cygnus.....	+29°4231	20 50.9	+30 2	...	Md	Variable. *UX Cygni*
Cygnus.....	+39°4368	20 51.6	+39 55	7.2	Cont.	
Cepheus.....	+64°1527	21 17.3	+64 27	5.5	B Pec.	*Hβ* bright
Pegasus.....	+24°4462	21 40.0	+24 33	...	Md	Variable. *RR Pegasi*
Cepheus.....	+61°2246	22 2.1	+61 48	6.0	Pec.	
Cepheus.....	+58°2402	22 8.1	+58 56	5.6	Pec.	λ *Cephei*
Cetus.....	−15°6531	23 57.0	−15 14	...	Md	Variable. *W Ceti*
Cassiopeia....	+54°3103	23 58.3	+54 60	7.9	Pec.	*Hβ* bright

[1] *Harvard College Observatory Circular* No. 92.

has recently been determined, and two additional objects found by other observers, as stated in the remarks following the table. The constellation and catalogue designation are given in the first two columns. The approximate right ascension and declination for 1900, and the catalogue magnitude except in the case of variables, are given in the third, fourth, and fifth columns. The class of spectrum and a brief description of the object are given in the sixth and seventh columns. The designations for stars north of declination $-23°$ are taken from the *Bonn Durchmusterung*, for stars between declinations $-23°$ and $-52°$ the *Cordoba Durchmusterung* is used, and for stars south of declination $-52°$ the *Cape Photographic Durchmusterung* is used. Each of the new variables has been confirmed independently by a second observer. Additional information regarding several of these objects will be found in the remarks following the table.

REMARKS

h m

4 32.8. This star varies probably more than three magnitudes, being as bright as the magnitude 9.0 on one of the plates examined, and fainter than 12 on two plates.

5 25.1. The spectrum of this star is between Classes K and M, and shows a bright line of slightly shorter wave-length than $H\delta$. The plates examined show a variation of about 0.7 magnitude, and, as in the case of the other stars, the variation has been confirmed by a second observer.

6 16.8. On a plate taken on October 16, 1904, with the 11-inch Draper telescope, the hydrogen line $H\beta$ is bright, $H\gamma$ is very faint and double, and the remaining lines of hydrogen and those of helium appear to be double. This is probably a spectroscopic binary. The spectrum of $-11°1478$, which is also on this plate, shows well defined single lines.

8 56.2. This spectrum extends beyond $H\epsilon$, having, besides the usual dark band in fourth type spectra, a second strong band near wave-length $H\delta$, and a third, between $H\delta$ and $H\epsilon$.

14 58.8. This spectrum shows the same peculiarities as that of the star, R.A. $8^h\,56^m.2$.

18 29.5. This spectrum has a broad dark band which extends from about λ 465 to 471, and is of the same type as *C.DM.*$-47°6614$, described in Circular No. 76.

18 52.4. This spectrum is already known as peculiar, but is inserted in the table in order to describe it as belonging to the same type as *C.DM.*$-47°6614$, described in Circular No. 76.

19 8.5. This star was the comparison star "o" in the sequence selected for *RW* and *RX Sagittarii*, and during the observations of these stars the variation in this star was discovered by Miss S. E. Breslin.

20 9.8. An examination of 16 chart plates shows a variation of about a magnitude in this star.

20 51.6. On a plate taken on September 15, 1904, the spectrum of this star is continuous, and fails to show any trace of lines, although the lines in other spectra are well defined. On some of the other plates the hydrogen lines show faintly, even with the spectrum not so well defined.

21 17.3. On a plate taken on October 16, 1904, with the 11-inch Draper telescope' the hydrogen line $H\beta$ is bright, the other lines are broad, and the spectrum has the same general appearance as that of the star. R.A. $6^h\ 16^m8$, although the lines in this spectrum do not appear double.

22 8.1. λ *Cephei.* The star ζ *Puppis* has a spectrum that heretofore has been regarded as unique. It contains, besides the usual series of hydrogen lines, a second rhythmical series also probably due to hydrogen, and only a few other lines. The southern declination of this star has rendered it difficult to study its spectrum at the great observatories in Europe, or in the United States. The spectrum of the northern star, λ *Cephei*, was found by the writer to be identical with that of ζ *Puppis.*

23 58.3. The hydrogen line $H\beta$ is bright and superposed upon a broad dark line. The lines $H\gamma$, $H\delta$, and $H\epsilon$ are narrow, and two other narrow lines having the approximate wave-lengths 416 and 420 are also present.

The variability of *C.P.D.*$-73^\circ 1134$, R.A.$=13^h\ 13^m5$, Dec.$=-73^\circ\ 55'$ (1900), suspected by Kapteyn, has been discovered independently by Miss L. D. Wells, and shows a range of about a magnitude and a half.

EDWARD C. PICKERING.

DECEMBER 21, 1904.

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